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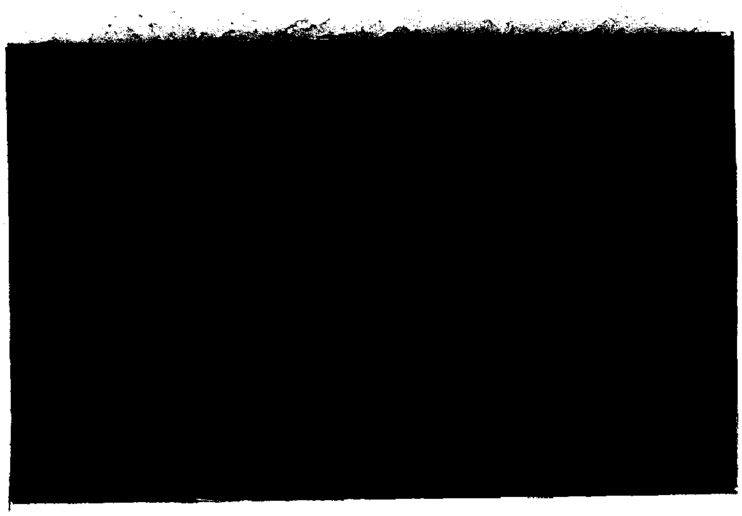

THE
JOHNS HOPKINS
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DEPARTMENT OF GEOGRAPHY AND ENVIROMENTAL ENGINEERING

Calvert Cliffs Slope Erosion Project
Phase I Final Report

Processes and Controls of Coastal Slope Erosion

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Executive Summary

More than one-half of the shoreline of Calvert County, Maryland consists of steep, actively eroding slopes 10 m to 35 m high. This slope erosion presents numerous environmental, safety, and economic problems. A particular concern is the response of the cliffs to a rise in sea level, which would accelerate cliff recession by allowing wave erosion and slope undercutting to work at higher locations on the cliffs. An adequate prediction of the cliff response to sea level rise requires an understanding of the mechanisms by which the cliffs erode and the critical environmental factors that determine the type and rate of slope erosion.

This report presents the results of the first year of the Calvert Cliffs Slope Erosion Project (CCSEP), a three-year collaborative effort between the Maryland Geological Survey and the Department of Geography and Environmental Engineering at the Johns Hopkins University. The overall goal of the Calvert Cliffs Slope Erosion Project (CCSEP) is to develop a quantitative understanding of slope erosion that can be used to predict past or future slope failures. The goal of the first year of the project is to to characterize the slope materials and types of slope failures presently occurring along the tall coastal cliffs of Calvert County. This information provides the basis for quantitative modeling of slope failures and recession in the latter two years of the project. In the second year, the individual factors contributing to slope erosion—wave undercutting, groundwater flux, surficial erosion, and slope stability will be modelled. In the final phase of the project, these models will be integrated to provide quantitative guidelines concerning the response of slope erosion to changes in external factors, particularly sea level change.

Four sites have been selected for detailed study. These sites are representative of the slope materials and erosion along the Calvert Cliffs. Each site has been further subdivided into several subsites so that a larger range of slope conditions could examined in an efficient manner. A summary of the geotechnical properties of the cliff materials has been prepared based on field observations, the logging of 22 groundwater observations wells, and the laboratory testing of samples taken from the four cliff study sections. The types and rates of slope erosion were measured using repetitive field observations and surveys of slope profiles at multiple sites for each of the four study sections. The heart of the report is Section Three, which characterizes the slope materials and types of slope failures along the Calvert Cliffs using a detailed description of the slope geometry, groundwater, geotechnical properties, and observed erosion at each study site.

A wide variety of slope erosion processes operate simultaneously on these steep, rapidly eroding slopes. These include direct wave removal of material at the slope toe, block falls along tension cracks, undercutting by groundwater seepage, surficial erosion by seepage discharge and surface wash, simple falling of material from near-vertical slopes, flow of saturated material during freeze/thaw cycles, shallow sliding of saturated surface material, and deep-seated rotational slides. Because of the number and complexity of these processes, we have developed a classification system for the cliff slopes based on the typical groups of erosion mechanisms and rates and their associated slope profiles. The classification system provides a basis for organizing a highly complex physical situation and serves to organize field experiments in the latter years of CCSEP. These experiments are designed to determine the critical values of environmental factors determining the different types and rates of slope erosion. Because the classification system is based on the erosion mechanisms that occur on individual slopes, it also provides the basis for designing and evaluating erosion mitigation projects and predicting slope response to changes in sea level and wave activity.

The slope classification system is based on two observations. First, a permanent seepage zone is found to occur on all cliffs in the range of 2 m to 15 m above beach level. Second, the geotechnical properties and resistance to erosion of the material above and below the seepage zone are found to be generally different. Below the seepage zone, the materials tend to be permanently moist, dark-colored, and massive in structure. These materials tend to be more resistant to surficial erosion than the overlying materials and fail primarily by direct falling from slopes oversteepened by direct wave activity. Within and above the seepage zone, the materials tends to be more granular in structure and more susceptible to surface erosion. These materials fail by a variety of mechanisms, but only occasionally by fracturing and falling driven directly by wave steepening of the slope. The slope classification system is organized according to the relative recession rates of the lower and midslope sections. Four slope types are recognized:

(I) Zero or minimal slope toe recession, allowing slope debris to build a depositional and vegetated lower slope. The lower slope stands at a smaller angle than the upper portions of the slope.

(II) Wave erosion removes accumulations of slope debris at the toe, but produces little, if any erosion of intact slope material. These slopes tend to be relatively straight, with minor slope variations appearing at boundaries between different stratigraphic materials.

(III) Wave erosion removes both toe debris and intact material at a rate sufficient to cause oversteepening of the lower slope and erosion by direct falling of the lower slope material. Despite the accelerated rate of lower slope recession relative to Type (I) and (II) slopes, midslope erosion driven by seepage discharge, surface wash, or gullying causes recession of the midslope to proceed even more rapidly than the lower slope, producing a characteristic decrease in slope angle at the boundary between lower and midslopes.

(IV) Wave-driven recession of the lower slope proceeds sufficiently rapidly that the midslope also becomes oversteepened and fails by spalling and shallow sliding. Deep-seated rotational slips can occur on slopes with sufficient height above a weak zone that is susceptible to elevated pore pressures. Type IV slopes tend to be relatively straight and much steeper than those of other types.

All categories of slope type are found within our study sites. In general, individual slopes can be readily placed within the slope classification system based on the characteristic slope geometry associated with each slope type. The slope measurements we have made to date indicate that the slope angles characteristic of the four basic slope types fall into distinct, nonoverlapping groups. This is a potentially important and useful result. Our slope classification is based on observations of groups of erosion processes and rates that typically occur together, and on the slope geometry developed by these groups of processes. If the type of slope can be determined based on the overall slope angle, the classification of individual slopes can be done quite readily. Once classified into a particular type, the erosion mechanisms acting on that slope, and the environmental factors controlling that erosion, can be estimated. Classifying slope type by angle can also provide the opportunity to make classifications from aerial photographs or detailed maps.

Type III slopes are the most common along unprotected sections of tall cliffs in Calvert County. Because recession of the middle and upper portion of Type III slopes is driven by hydrologic erosion processes related to seepage discharge and surface flow, it is clear that environmental factors other than wave undercutting can determine the type and rates of slope erosion acting at any one location. This point is particularly evident at two of our study sites, where direct wave undercutting has been prevented by man-made structures. At both sites, active erosion of the middle and upper slopes continues, despite the fact that toe erosion has been prevented for decades. An understanding of slope erosion along tall cliffs, such as those in Calvert County, clearly must include the erosion driven by seepage discharge and overland flow.

A summary of erosion rates measured over the last 140 years is provided in this report and compared to the short term processes investigated here. The distribution of sediments with similar properties along other portions of the Maryland Chesapeake Bay shoreline is given to provide a basis for extrapolating the erosion mechanisms and slope types observed in Calvert County.

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We are indebted to Jack Pomeroy for introducing us to the sites along the Calvert Cliffs and the erosion mechanisms operating there, and to Peter Vogt for his perspectives on the erosion processes and stratigraphy of the cliffs. Our thanks are extended to Commanders Jones and Kummer and Mr. Tracy Erwin of the Naval Research Laboratory, Chesapeake Bay Division for their cooperation in establishing a study site there; to the Honorable David Bonior, the Walter Lippold family, and Ms. Ruth Shinn for granting us permission to install and monitor groundwater wells on their property; and to Mr. John Westerfield for his assistance in establishing a study site at the Calvert Cliffs State Park. Thanks are also in order to Mr. Dick Mulford and Ms. Carole Yatchum of the Scientists' Cliffs Association and Property Owners Association of Chesapeake Ranch Estates, respectively, for facilitating our activities at our study sites.

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1. Introduction

1.1 Background

The open shoreline of Calvert County, Maryland extends 45 km along the western side of the Chesapeake Bay. Of this shoreline, 65% consists of steep slopes 10 m to 35 m high. Most of these slopes, well-known as the fossiliferous Calvert Cliffs, are actively eroding. Slope recession rates greater than 2.5 m/yr over a 96 year period have been measured along the Calvert Cliffs (Slaughter, 1949). This slope erosion presents numerous environmental, safety, and economic problems. Sediments eroded from the cliffs contributes to increased sedimentation and turbidity in the bay. Pollution from septic leachate is a growing problem where slope recession approaches septic fields. Direct undercutting of homes and civil structures incurs large personal and social costs. Shore erosion control measures designed to protect slopes from undercutting and further recession are very expensive and difficult to finance by private or community funds. Slope failures also create a personal safety problem in areas of public access, such as the Calvert Cliffs State Park. Adequate safety guidelines, development plans, and remediation programs all require a reliable understanding of the type, timing, and rate of slope erosion and of the environmental factors which control slope instability.

Population growth in Calvert County and nearby metropolitan areas has maintained a continued pressure for development of property along the Calvert Cliffs. At the same time, interest in protecting the Chesapeake Bay and its shorelines as a natural resource has resulted in the passage of the Chesapeake Bay Critical Areas Act, which implements strict guidelines limiting development of land within 1,000 feet of tidal water and tidal wetlands and requires the maintenance of a 100 foot intact buffer. Reasonable application of these guidelines in planning future development, particularly at the case-by-case level, as well as protection of existing development, requires reliable information concerning the rates, timing, and type of shoreline erosion and the environmental factors which control it.

One driving mechanism for the slope recession observed over the past 150 years is a slow rise in sea level, causing wave erosion and slope undercutting to work at progressively higher locations on the cliffs. The change in sea level in the Calvert County area over the past 150 years is not precisely known, but appears to fall within the rates of 1.5 to 4 cm/decade (Emery and Aubrey, 1991). It is clear that future increases in sea level would compound the existing erosion problem and accelerate the long-term recession rate.

Estimates of slope recession over a period of 100 years have been prepared from an analysis of historical maps and modern aerial photographs (Slaughter, 1949). These efforts are currently being updated and extended over an additional 45 years by the Maryland Geological Survey. Because the the type and rate of slope erosion can vary locally, and because slope erosion can be cyclic, with periods of little erosion followed by periods of intense erosion,(Quigley et al., 1977), it is difficult to apply the regional, historical slope recession rates to short-term planning, safety guidelines, or remediation plans for specific sites. It is also difficult to use past erosion rates to predict future slope recession if the basic driving forces—the bay water level and wave activity—change in the future. The goals of the Calvert Cliffs Slope Erosion Project are to develop an understanding of the slope erosion mechanisms and rates based on the local slope and shoreline characteristics, and to determine the environmental factors that control slope erosion on a site-specific basis. Because local cliff properties control the response of individual slopes to undercutting, the information collected in this project, and the slope erosion models developed from that information, should be valuable for local planning and remediation. Because the results of this project incorporate the mechanics of the slope erosion, we can address how the slopes will respond to conditions that differ from those acting during the three year project, or over the past 150 years. The local, mechanics-based approach followed here, and the regional, historical approach work well together. The first provides explanation, local application, and predictive capabilities to the second, while the second provides measured limits to the short-term processes involved in the first.

1.2 Overview of the Calvert Cliffs Slope Erosion Project

The overall goal of the Calvert Cliffs Slope Erosion Project (CCSEP) is to develop a quantitative understanding of slope erosion that can be used to predict past or future slope failures. This understanding will be developed in a three-step process. First, the erosion mechanisms occurring at each study site must be identified. Second, the environmental factors controlling these particular erosion processes must be determined, based on our understanding of the erosion mechanics, the geotechnical properties of the soil and slope, the pore pressure regime of the slope, and the wave and precipitation driving forces of the erosion. Third, critical values of the environmental factors controlling slope erosion determine the types of erosion and their relative importance at each site and will be quantified through the development and testing of quantitative models of the slope erosion for each study site.

These models will tested in two ways, one absolute and one relative. First, predictions of types and rates of slope erosion may be directly compared with field observations. These tests are direct and useful, but limited by the fact that coastal slope erosion typically occurs over periods of time much longer than this study, and by the amount of error inherent in predicting the rates of complex physical processes. The first problem is partially addressed by extrapolating our predicted results over a much longer time frame and comparing the result with historical observations of slope recession over the past 150 years. The second test is a relative one and is based on comparing predicted results between individual sites by means of field experiments. We define field experiments as a pair of slopes between which there is a significant variation in one environmental factor of slope erosion and a much smaller variation in the other controlling factors. Our ability to predict differences in behavior between two sites is often better than our ability to predict the absolute rates at an individual site. By examining and modelling pairs of sites where there is a significant variation in only one slope erosion factor, we can test our modeling by comparing prediction vs. observation of the contrast in slope erosion between the pair. For cliffs that are actively eroding, such as at Calvert Cliffs, this second test allows us to identify critical values of the factors that control slope erosion. These models, together with an understanding of critical values of erosion controlling factors, allow us to estimate slope erosion types, rates, and timing at each study sites.

The goals of Phase I of CCSEP are to accomplish the first two tasks. We have identified the the suite of erosion processes currently occurring along the cliffs. We have developed a data base of geotechnical and slope geometry information. These data are then used, together with a mechanical description of each erosion process, to identify the controlling factors of coastal slope erosion in Calvert County. An important factor limits our ability to completely characterize the slope erosion controlling factors at each study site. Funding restrictions prevent a study of the wave energy distribution in front of the cliffs to the level necessary to identify wave energy flux and undercutting rates driving the slope erosion at each study site. Our description of the effect of undercutting on slope erosion focuses more on protected vs unprotected slopes and, for unprotected slopes, uses the elevation of the beach and slope toe and the cliff orientation as a surrogate for wave erosion energy.

Information on slope materials, groundwater flow, and wave conditions will be combined with the slope erosion observations to develop a slope erosion model that can be used to predict the response of slopes to future changes in sea level. Because the model will operate a site-specific level, and because it will be based on the mechanisms and controlling factors of coastal slope erosion, it will also provide a basis for designing and evaluating shore erosion hazard mitigation projects.

1.3 Overview of Phase I — CCSEP

This report describes the mechanisms, rates, timing, and environmental controlling factors of cliff erosion in Calvert County. These are the results of the first phase of the Calvert Cliffs Slope Erosion Project (CCSEP). The objective of Phase I of CCSEP is to characterize the slope materials and types of slope failures presently occurring along the tall coastal cliffs of Calvert County. Four sites have been selected for detailed study. These sites are representative of the slope materials and erosion along the Calvert Cliffs. A summary of the geotechnical properties of the cliff materials has been prepared based on field observations, the logging of 22 groundwater observations wells, and the laboratory testing of samples taken from the four cliff study sections. The types and rates of slope erosion were measured using repetitive field observations and surveys of slope profiles at multiple sites for each of the four study sections. From these data, we have developed a summary of the types, timing, and magnitude of slope failures. The slope profile and geotechnical data are used to summarize the influence of geotechnical properties on slope erosion. The distribution of geotechnical properties and slope failures at the Calvert Cliffs are used to extrapolate the observed effects of geotechnical properties on slope failure to other regions in the Calvert Cliffs and to other parts of the Chesapeake Bay coastline where the same types of sediments are found.

2. Site Selection

2.1 Controlling factors of coastal slope erosion

A basic objective of this project is to identify the slope erosion mechanisms and the critical values of the environmental factors that control the types and rates of the slope erosion. By knowing how the slopes erode and what controls the erosion at individual locations, we can begin to predict how the slopes will respond to future changes in the basic driving forces. This section briefly outlines the environmental controlling factors of slope erosion and explains how we will use field experiments to identify the critical values of these controlling factors at particular locations.

The environmental factors controlling coastal slope erosion may be organized into four basic categories: slope geometry, hydrology, material properties, and basal undercutting.

1. Slope geometry - The stability of a slope depends in part on its spatial dimensions, particularly slope height, and the geometric shape of the slope. The geometry controls the total stresses developed in the slope and, in conjunction with the pore pressures generated by groundwater flow, controls the shear strength that can be mobilized within the slope. Slope geometry also controls the gradients of runoff over the slope surface, and therefore the erosive force supplied by surface water. The pattern of groundwater flow within the slopes is also partially controlled by slope geometry.

2. Hydrology - Slope erosion produced by both surface runoff and groundwater seepage has been observed along the Calvert Cliffs (Leatherman, 1984). Surface runoff generated by precipitation on the slopes can directly erode material. Surface runoff can also saturate and weaken near-surface materials and contribute to shallow sliding. Erosion from surface runoff can also be generated by groundwater seepage on the slopes. Seepage may occur along a strata, which we call sapping, or at concentrated points, called piping. In both cases, sediment may be directly eroded at seepage outlets, which results in undercutting and erosion of overlying strata. The effective strength of materials against deep-seated slope failures in the slopes depends in part on pore pressures related to groundwater flow within the slope.

3. Material properties - Material strength and resistance to erosion depend on properties such as grain size and sorting, cohesive strength, and material internal friction. The Calvert Cliffs are composed of interbedded fossiliferous sands, gravelly sands, silts, and clays. Ironstone, a particularly strong type of rock that occurs in the sediments composing the Calvert Cliffs, forms in laterally discontinuous patches and is the hardest material present in the slope materials. Due to the variety of materials, there are large contrasts of material strength between stratigraphic units. Because these units dip gently along the shoreline, there are also contrasts in material strength along the cliffs.

4. Undercutting by waves - Waves actively cut into the intact slope material at the cliff base and also remove eroded debris from the slope toe. Wave action is controlled by several factors, including shoreline orientation, elevation of the slope toe, near-shore bathymetric configuration (including offshore sand bars), variations in water level, shoreline protection, and wind speed, duration and fetch (fetch is the water surface area available to the wind on which waves can be formed).

2.2 Selection of study sites

The following criteria were used in the site selection process:

1. Taken together, the sites must represent the range of hydrology, material type, wave climate, cliff geometry, and modes of failure found at Calvert Cliffs.

2. The sites must be accessible and property owners must be amenable to the requirements of all proposed activities.

3. The properties of individual sites must permit between-site comparisons in which a large variation in one factor of slope instability is observed along with only minor variation in all of the other controlling factors. Each such comparison comprises a field experiment that will help us define the critical values of the environmental factors controlling slope instability along the Calvert Cliffs.

Four study sites were selected along the Calvert County shoreline. Each site was divided into several subsites so that the number and diversity of field experiments could be as large as possible. Each site is named after a feature near its geographic center. Some slope controlling factors are common to all of the subsites within each site. For instance, stratigraphic horizons maintain a nearly uniform material composition across each study site. The sites are shown on Figure 2.1. Listed from north to south their names and acronyms are:

1.	The Naval Research Lab	(NRL)
2.	Scientists' Cliffs	(SC)
3.	Calvert Cliffs State Park	(CCSP)
4.	Chesapeake Ranch Estates	(CRE)

2.3 Field experiments

Each study site represents a particular combination of the factors controlling slope erosion. Some of these factors may not remain constant in time. Three of these controlling factors (slope height, material properties, and wave undercutting) are suitable for defining our field experiments because they may be reasonably considered to be independent variables in the slope erosion problem. That is, they may be considered as given for a particular cliff section, allowing us to reliably compare two sections between which only one of these controlling factors differs. In order to determine the critical values of these controlling factors, our site selection process was designed to identify pairs of sites for which there is a significant variation in only one factor. The fourth factor, slope hydrology, has an important influence on slope erosion, but the variation in hydrologic input (snow and rain) over the Calvert Cliffs area is negligible, so that field experiments in which the hydrologic input varies cannot be defined. Instead, we must carefully monitor precipitation, runoff, and groundwater flow at each site in order to measure the effect of slope hydrology on erosion. Other controlling factors of slope erosion, such as slope shape, may be considered dependent variables. Although slope shape influences the slope stability at any particular time, the shape itself depends on the combination of slope height, material properties, wave undercutting, and precipitation that have existed at that site over time.

The field experiments we have been able to define to date are listed in section 4.4 of this report, following detailed descriptions of the study sites, the ongoing erosion mechanisms, and their environmental controlling factors.

3. Description of the Study Sites

3.1 Survey Methods

Slope Surveys

Surveying instruments used during the course of Phase I included:

1) Lietz/Sokkisha SET3 - electronic total station (serial # 84121)

Vertical Accuracy	5"
Horizontal Accuracy	2"
EDM Accuracy	± (5mm + 3ppm x distance (m))

2) Lietz/Sokkisha DT20E Theodolite - electronic digital theodolite (serial # 60619)

Vertical Accuracy	20"
Horizontal Accuracy	20"

3) Topcon AT-F6 Auto Level (serial # X60457)

Accuracy in 1 Km in double run leveling	±2.0 mm

Elevation Surveys

All elevations were established relative to the 1929 National Geodetic Vertical Datum. The double run leveling method was used to perform all elevation transects. Elevations were established for the well heads and surveying reference stations using the Topcon level and a level rod. Elevations for slope survey instrument stations were established from surveying reference stations using the SET3 total station distance ranging feature.

U.S. Coast and Geodetic Survey benchmarks were used directly for all of the elevation transects except the transect at the Chesapeake Ranch Estate site. There, the elevation of a public water supply well head at well site No. 3 was used. The elevation at this well head was established in reference to 1929 NGVD by the Maryland Department of Natural Resources, Technical Services Division and designated "Ca-Fe 18". A list of the benchmarks used to establish elevation at each site follows.

Site	Benchmark
Naval Research Lab	Navy (reset 1971)
Scientists' Cliffs	U133 (reset 1971)

Calvert Cliffs State Park	Cove B.M.
Chesapeake Ranch Estates	Ca-Fe 18

Horizontal control

Horizontal control was not referenced to a general horizontal network. Instead, it was maintained locally at each study site, typically referenced to a unique, obvious, and permanent feature.

Slope Profile Surveys - all sites

Open traverses were used to establish baselines along the shoreline for the horizontal control used in slope surveys. Accurate and efficient closed traverses were virtually impossible to complete due to the nature of the slope topography. Except for slope survey instrument stations on protected slope toes, instrument stations could only be temporarily established due to washover by high tides. Therefore, baselines had to be established each time a survey was made.

A typical slope survey was performed using both the SET3 total station and the DT20E theodolite. The instruments were set up two to three meters apart. Both instruments sighted on identical points along a slope profile. Triangulation was used to establish the horizontal and vertical position of individual points on the slope. The distance ranging feature of the total station was not used because safe access for positioning the reflector was restricted to the slope toe and bluff top region. One instrument was located along a profile line and the horizontal angle was set for that machine so that it was perpendicular to the slope toe. This angle remained unchanged during the course of the survey. Points along the slope surface and on this profile line were selected and the angles to each point from both machines were recorded.

Field Observations and Photo Stations

In addition to repetitive slope surveys, regular site visits are made to observe changes in the slope geometry, seepage condition, and shoreline configuration. During each slope survey and when visual inspection indicates significant changes have taken place, the slopes are photographed from fixed stations established during the initial baseline surveys.

3.2 Geotechnical Methods

Stratigraphic Description, Well Logging, and Sample Collection

Prior to establishing groundwater monitoring wells, a preliminary survey of the slope profile adjacent to each well site was conducted. A detailed stratigraphic description was then made at the cliff face along the surveyed profile. For those stratigraphic units buried by debris or located in the inaccessible upper cliff, descriptions were made of the same unit as close as possible to the surveyed profile. The stratigraphic description of each unit included information on the strength, color, thickness, grain size, moisture content, hydrology, paleontology, sedimentary structures, and vegetative surface cover. All elevations are referenced to the 1929 National Geodetic Vertical Datum and elevations associated with stratigraphic intervals are given where they occur in the sampled borehole at each site.

A total of twenty-two groundwater monitoring wells were drilled over the period from 6 December 1990 to 1 February 1991; six at the NRL, five at SC, six at the CCSP, and five at the CRE. They were drilled using a rotary drill rig owned and operated by the State of Maryland, Department of Natural Resources, Water Resources Administration, Technical Services office. The drilling was done using a hollow stemmed auger through which a standard penetration test (SPT) was performed and a split-spoon sample obtained, each at five foot intervals. The penetration tests and sampling were done in the first (and deepest) well drilled at each site.

The SPT is a reliable, widely used method for estimating the relative variations of in-situ, undrained shear strength of subsurface cohesionless materials. For strongly cohesive materials it provides a somewhat less reliable, but useful, estimate of the stiffness (cohesive strength) of the unit. The results of the SPT are reported as the number of blow counts required to drive the split-spoon sampler the final twelve inches of each sampling interval. The blow count is corrected for overburden pressure as specified in the procedure for the SPT. The SPT data is presented graphically on the geotechnical diagram for each site. These diagrams permit an immediate evaluation of the relative strength of each stratigraphic unit at each site.

Split-spoon samplers are driven 1.5 feet vertically downward, ahead of the auger bit. Upon retrieval, each sample is described and a representative portion or portions is obtained for laboratory analysis. The field description includes information on the color, grain-size, fossil content, and moisture content.

Laboratory Analysis

A grain size analysis was performed at the Maryland Geological Survey's sediment laboratory on 70 samples taken from the split-spoon. For split-spoon samples which spanned more than one stratigraphic unit, each unit was analyzed. The information is graphically presented on the geotechnical diagram for each site as percentages of gravel, sand, silt and clay . A tabular presentation of the grain size analysis is provided in Appendix A.

A summary of the procedure used by the Maryland Geological Survey for grain size analysis follows:

1. Approximately thirty grams of the material are mixed with 300 mL of 10% hydrochloric acid (HCl). The HCl is allowed to remain in contact with the material for 24 hours to dissolve the calcium carbonate contained in the sample. The sample is then rinsed with deionized water.

2. Approximately 300 mL of 15% hydrogen peroxide (H2O2) is added to the sample to remove organic material. The sample is allowed to react with the H2O2 for twelve hours and then it is heated at 100° C until the reaction is observed to be negligible. The sample is then rinsed with deionized water.

3. 0.3% sodium hexametaphosphate, a dispersant, is added to deflocculate the silt and clay particles. After twelve hours each sample is passed through a 63 micron sieve to separate the sand and gravel from the silts and clays. The portion which passes through the sieve is transferred to a graduated cylinder and deionized water is added to the 1,000 mL mark. The mixture is agitated thoroughly and two samples are taken to determine the amount of silt and clay respectively. The first sample is taken at 20 cm depth after 20 seconds and the second at 5 cm depth after approximately one hour. The exact time interval between samples depends on the temperature of the suspension.

4. The samples and the sand and gravel remaining on the 63 micron sieve are dried and weighed. The gravel is separated from the sand by passing it through a 2 mm sieve, and the total weight fractions of each of the gravel, sand, silt and clay are determined.

Laboratory analysis determined that most of the sample weight loss occurred during the HCl digestion and was due to the dissolution of calcium carbonate shells and shell fragments. Therefore, the weight loss provides a good indication of the presence of shell beds and is included on the geotechnical diagrams for each site.

3.3 Description of Erosion Mechanisms

Because particular groups of erosion processes tend to occur together at different elevations on the slopes, we have found it useful to organize these mechanisms and their controlling factors according to three cliff sections: lower, middle and upper. Along the length of the Calvert Cliffs, two conditions exist in the toe zone: the intact slope material may be exposed to direct wave activity or may be covered with debris eroded from the slope above. Regardless of the two conditions, a feature common to all slopes is that the intact material comprising the lower zone of the slope is moist or saturated and distinctly darker colored than the slope above. The upper boundary of this zone is defined by a seepage layer that seeps year-round or continuously during wetter periods. On slopes where debris has accumulated in the toe zone, the dark, wet material of the lower slope is often completely covered. The erosion mechanisms acting on the lower slope are directly related to wave activity and, in many cases, are different from the erosion mechanisms acting on the middle section of the slopes. The latter are often controlled by local surface water and groundwater, slope geometry, and material strength. Similarly, the types of erosion types acting on the middle portions of the slope generally differ from those acting on the upper portions of the slope. In the upper slope root mats, soil development, and weathering act to strengthen the slope, which often stands at a very steep angle, and erodes by debris falls in response to direct undercutting.

The wave dominated lower slopes erode by

(a) surficial erosion (direct wave action; freeze/thaw; surface wash) or

(b) spalling (intact blocks of material separate from the slope along nearly vertical cracks and eventually fall as a block onto the beach below) in direct response to undercutting

Hydrologic processes tend to dominate in the mid-slopes. Erosion caused by hydrologic processes occurs by

(a) slumps along deep-seated failure zones. Typically, slumps are found above the perennial seep in tall cliffs (> 25 m). They are often rotational and result when groundwater pore pressures cause materials to weaken to critical levels. Important slope parameters include slope height, slope angle, and pore pressure.

(b) removal of surface material by overland flow. The source of water may be

(1) seepage, which may occur in

relatively continuous sapping zones, which tend to produce a more uniform lateral topography below the seep, or as piping outlets, which produce a more concentrated flow and contribute to mid-slope gullying

(2) direct surface runoff of precipitation, which tends to produce gullying beginning at the top of the slope.

(c) undercutting by seepage erosion and failure of the overlying layers.

Although erosion of the midslope is most commonly accomplished by hydrologically driven processes, at some locations (Randle Cliffs, Parker Creek), the rate of wave-driven recession of the lower slope may exceed that due to hydrologically driven erosion of the midslope, causing oversteepening of the mid-slope, which results in spalling of relatively fine-grained materials, or shallow sliding in coarser units.

Gravity driven failures along desiccation cracks and root channels tend to dominate in the upper mid-slope through the bluff top. Failures characteristic of this type of slope recession are

(a) collapse of soil fragments from near vertical slopes

(b) columnar fracturing and toppling

(c) collapse of overhung root mats

The upper slopes often stand close to vertical because of increased cohesion due to clay deposition in the root zone and binding by roots. The root mat may even create an overhang at the slope top. Because slope recession is driven from below, the recession of the upper slope ultimately depends on the erosion rates of the lower and middle slopes. The slope angle at which the upper slope can stand, the period of time at which it may stand close to vertical, and the degree of overhang the soil and roots can maintain, are all limited. If the lower slope and midslope recedes, the upper slope will eventually fail. Local factors controlling erosion of the upper slope cannot prevent recession of the slope top, although they tend to make the recession episodic.

3.4 Naval Research Laboratory

General Site Description (Figures 3.1, 3.2)

The site encompasses the shoreline and cliffs from Randle Cliffs to Holiday Beach. The subsites are Randle Cliffs (RC), Naval Research Lab North (NRLN), Naval Research Lab South (NRLS), and Holiday Beach (HB).

The cliffs are uniformly oriented east-northeast along strike, except at Randle Cliffs where they face due east. Shore protection exists in the form of a seawall in front of the Naval Research Laboratory (subsites NRLN and NRLS). The shoreline is unprotected at the northern and southern ends of the site (subsites RC and HB). A series of sub-parallel longshore sand bars is present at both the northern and southern ends of the site (subsites RC and HB), but the bars are not evident along the portion of shoreline protected by the seawall.

The cliffs vary gradually between 18 and 27 meters in height along the Randle Cliffs subsite and have steep slope angles approaching 90 degrees. At NRL-North, the cliffs vary between 18 and 34 meters in height and the slope angle near the toe is shallow at 30 degrees, but increases to nearly vertical about five meters from the cliff top. Along NRL-South, the cliff height is consistent at 31 meters and the slope angles are similar to NRLN. At Holiday Beach, cliff height varies gradually from 20 to 34 meters and the slope angle maintains a uniform 70 degrees from toe to top.

The site lies entirely within the Miocene Calvert Formation. All stratigraphic units dip gently to the southeast. Stratigraphic units located near the cliff top at the north end of the site gradually descend toward beach level at the southern end. At Randle Cliffs, a heavily diatomaceous clayey-silt layer occurs in the tidal zone and gradually dips below beach level at NRL-North. Very little beach is present along the Randle Cliffs subsite with the cliff face extending below high water level in most places. Where the slope base is once again exposed to tidal action near Holiday Beach, there is beach present under most tide conditions. The cliff base is composed of a greenish-gray sandy clay known as marl. Across the entire site, the upper stratigraphic horizons of the cliffs are composed principally of a grayish-green sandy clay interrupted vertically by layers of somewhat sandier fossiliferous horizons. On the highest cliffs, a brown clayey sand is present.

At the Randle Cliffs and NRL-North subsites, surface water drains toward the cliffs over an area extending almost one km west of the cliff top. NRL-South and Holiday Beach subsites are located on hilltops which cause the surface water to drain in all directions. Across the entire site, groundwater seeps from the cliff face at the interface between a sandy shell bed overlying a sandy clay unit. There appears to be a greater volume of seepage where topographic lows intersect the cliff face.

Geotechnical Properties (Figure 3.3)

The cliffs at NRL are 12 to 34 m high and the materials which compose them may be divided into four major groups: a fine grained root zone with well developed soil horizons, and two extensive cliff segments composed primarily of sands separated by a 4.3 m thick series of silts and clays.

The soil horizons and the majority of the root zone extend from the cliff top, which at the well site is at 27.9 m in elevation, into a silty, sandy clay which is 1.5 m thick. From 26.5 m to 17.6 m the cliffs are composed primarily of moist, light brown to tan, leached and oxidized sands with increasing amounts of silt and clay with depth. The SPT indicates that the materials reach a minimum in undrained shear strength at an elevation of approximately 20.5 m.

At 17.6 m a change of grain size takes place from materials dominated by sands to a section approximately 4.3 m thick dominated by drier, greenish-gray to gray silts and clays. An intermittent seepage zone is evident at the base of the sandy units, because the fine grained silts and clays act as a barrier to the downward movement of water. The materials reach a peak strength in the silt and clay materials; however, it should be noted that the materials were dry when tested and are composed of cohesive materials which may behave very differently when saturated. The two clay units extending between 13.3 m and 16.8 m in elevation form columnar pillars which either topple or disintegrate into angular fragments.

Below the silty-clayey material at 13.3 m in elevation, lies a gray, saturated, sandy shell bed which is approximately 1.5 m thick. At the base of the shell bed is a seepage zone, which has been observed to be constantly seeping over the past 10 months.

Beginning at an elevation of 11.3 m and extending below the cliff base, the materials are composed of gray-green to green, dry to moist, sandy sediments that contain increasing amounts of fine-grained material with depth. During field mapping, the unit located between the elevations of 4.2 m and 11.3 m, composed of a gray-green, silty, clayey sand, was observed to be strongly jointed. The joint surfaces were visibly wet, acting as preferential flow paths for groundwater and creating planes along which block spalling takes place. Where this unit is exposed, it has been observed to spall year-round, although the frequency of spalling increases during freeze-thaw periods. The spalling tends to terminate near the contact of this unit with the shell bed above causing the shell bed to form an overhang in many places.

Erosion Mechanisms

Site/Subsite: Navy Research Lab/Holiday Beach

Lower Slope. Most of the toe zone is covered with a light mantle of unconsolidated upper slope debris generated on the upper slopes which forms laterally continuous, wedge-shaped deposits or larger triangular debris fans. Sparse, herbaceous vegetation has become established on the unconsolidated debris along most of the toe zone. Physical and chemical weathering result in disintegration of the silty, clayey, very fine sand which comprises the intact slope material along the toe zone. Daily waves and tides do not remove toe zone debris at this site. However, wave action due to strong winds and storms periodically removes the unconsolidated debris and erodes the intact slope.

Midslope. A nearly uniform, fairly gentle incline occurs from the base of the debris fans at the toe to the base of the root zone. A perennial seepage zone occurs at approximately 5 m above the beach where a shell bed with a gray, medium to fine sand overlies a gray-green clayey, silty, very fine sand. At locations where the topographic surface behind the cliffs is low, groundwater seepage tends to be stronger and keeps the slope face below moist. Below the seepage zone, the face is covered with a thin veneer of weathered debris which presents a uniform planar surface when viewed from a distance but, although closer inspection reveals that it is slightly rilled, indicating some erosion by overland flow. Above the shell bed seepage zone is a drier face composed of a gray, silty, sandy clay which coarsens upward to become a clayey, sandy, silt and is prone to fragmental disintegration primarily due to desiccation. Continuing upslope an ephemeral seepage zone is encountered where the clayey, sandy, silt meets a silty, clayey, fine sand. This seep periodically supplies water to the slope face below and when active, undercuts the bluff top by sapping erosion. (Sapping erosion is the erosion of slope materials by groundwater flow along a laterally continuous seepage zone).

Upper Slope. The bluff top is nearly vertical along this site with very little undercutting. The bluff top retreats by surficial erosion of weathered sediments and some root mass failures.

Site/Subsite: Naval Research Lab/ NRL North and South

Lower Slope. The entire length of the shoreline along the Navy property has been protected by a bulkhead for a period of 60 years. The slope toe is completely protected. The result is that toe debris has been allowed to accumulate at an angles of less than 35 degrees and become vegetated.

Midslope. Typically, the middle portion of cliffs along the Navy property is vegetated and inclined at a gentle angle composed primarily of unconsolidated upper slope debris. At the top of the mid-slope incline is an ephemeral seepage zone where a densely fossiliferous shell bed with a fine sand matrix overlies a green-gray, clayey, silty, very fine sand. Here, sapping erosion is prevalent. This erosion undercuts overlying units, causing them to fall. Field inspection of this seepage zone indicates that it is subject to both piping and sapping erosion when the seepage is active. Field strength tests indicate the shear strength of the materials comprising the cliffs to be at a minimum at the seepage interface. Seepage from the shell bed produces surficial erosion of weathered material from the slopes below. In this way, bluff top recession continues despite significant toe protection.

Upper Slope. The slope break between the midslope and upper slope is defined by an intermittent seepage zone. The bluff top recedes by an undercutting due to seepage, surficial erosion of weathered materials, and toppling of columns of material that separate from the slope along vertical stress-relief fractures.

Site/Subsite: Naval Research Lab/ Randle Cliffs

Lower Slope. The toe zone is composed of a green-gray clayey silt. The elevation of the toe zone is below mean low water and the toe zone is subjected to nearly continuous wave undercutting which results in spalling of large blocks from the nearly vertical lower slope. Removal of the slope debris is generally quite rapid; only debris from the largest slope failures remains on the beach for periods longer than several weeks to a month. Approximately half of the toe zone is devoid of slide debris at any time.

Midslope. The active wave undercutting and retreat of the lower slope tends to steepen the midslope sections, which initiates further spalling and shallow sliding in the midslope zone. This process of failures in the lower slope triggering additional failures in the overlying material, leading to a series of retrogressive failures at higher elevations has been described for other coastal slopes (Edil and Vallejo, 1977; Quigley et al., 1977). Typically, spalls work their way up the steep slope face to the perennial seepage zone where the lower sandy shell bed is located. Some spalls are sufficiently large that they extend from beach level to the perennial seep approximately 10 m above the beach. Undercutting and spalling tend to keep the slope face straight and nearly vertical. Above the seep, columnar slope sections separate from the face along tensional fractures and topple or fall to the beach. The columnar joints form in response to stress relief in the rapidly retreating slopes, as well as to the swelling and shrinkage associated with the wetting and drying of the material comprising the columns. Columns topple and fall when undercut by failure and retreat of the slope below them.

Upper Slope. Weathered and leached materials near the bluff top tend to fail in undercut slumps that bury earlier spalled material beneath. Undercut root zones eventually collapse in cantilever type failures.

3.5 Scientists Cliffs

General Site Description (Figures 3.4, 3.5)

The site encompasses the shoreline and cliffs from Parkers Creek to Governors Run. The subsites are Parkers Creek South (PCS), Scientists' Cliffs North (SCN), Scientists Cliffs South (SCS), and Governors Run (GR).

The cliffs are uniformly oriented east-northeast along the entire site. Beach protection exists in the form of uniformly spaced gabion groins in front of the Scientists Cliffs Community (SCN and SCS). These groins have produced a beach up to one meter higher than found at the subsites to the immediate north and south (PCS and GR). The beach at Scientists Cliffs appears to offer a significant degree of slope toe protection. The cliffs to the north and south of Scientists Cliffs (PCS and GR) have little or no beach at their toe, are generally devoid of vegetation, and are actively eroding, . The slopes are relatively steep along the Parkers Creek South subsite, standing at angles between 70 and 80 degrees. Slope height varies between 15 and 30 meters. The subsite at Governors Run has slope angles of 65 to 80 degrees and cliff heights between 18 and 36 meters. At both the Scientists' Cliffs North and South subsites, the slopes are thickly vegetated and slope angles vary between 45 and 60 degrees. However, the cliffs are generally taller at the southern subsite, ranging from 20 to 29 meters, while at the northern subsite, they range from 15-25 meters.

The sediments of this site consist of interbedded clays, silts, and sandy fossiliferous units of Miocene age. The Calvert Formation is found in the lower portions of the slopes and the Choptank Formation in the upper portions. All stratigraphic units dip to the southeast, although individual stratigraphic thicknesses are less uniform than elsewhere in the Calvert Cliffs. Spalling occurs near the cliff base at the Parkers Creek South subsite in a thick blue-gray silty clay unit. Stratigraphic horizons in the upper sections of the cliff tend to be leached and less cohesive than those below.

The surface topography of the site is characterized by a highly dissected drainage consisting of a series of hilltops separated by drainage channels. Groundwater seepage is evident along exposed cliff faces and tends to occur at the base of a sandy fossiliferous stratigraphic unit. Seepage volumes tend to be higher where topographically low surface areas intersect the cliff face.

Geotechnical Properties (Figure 3.6)

The cliffs at Scientists' Cliffs range between 15 m and 36 m in height. The stratigraphic profile consists of five material groups at this site. The root zone and soils are developed in a silty, very fine sand. A weathered clay separates the sandy soils above from another thick sequence of sands containing shell beds below. About mid-slope the sands are interrupted by a thick, clayey, sandy silt. Beneath the silt lies another shell bed and series of fine to very fine sand units. This sequence continues uninterrupted to the cliff base and below.

The surface elevation at the well head is 26.9 m. The matrix in the soil horizons and root zone is composed of an orange, very fine sand. The amount of silt and clay increases with depth to an elevation of 23.4 m where a unit composed predominantly of clay is present. It consists of a series of tan and gray clays and extends to 21.7 m where a sandy shell bed is encountered. The 4.2 m thick shell bed is quite porous and permeable. SPT blow counts indicate that it has the highest strength of all the stratigraphic units in the entire Scientists' Cliffs profile. At its base the shell bed grades into a non-fossiliferrous, brown, medium sand, approximately 1 m thick.

The base of the brown sand lies at an elevation of 17 m on a noticeably finer grained, dry, gray, silty sand creating a permeability contrast which gives rise to intermittent seepage on the cliff face. Erosion due to seepage in this material is responsible for undercutting the bluff top, causing it to fail under its own weight. The brown sand and the underlying gray silty sand are the weakest units in the profile as indicated by the SPT.

From the base of the medium brown sand, the silt and clay contents increase for approximately 6 meters reaching a maximum in a gray, clayey, sandy silt which extends to an elevation of 11 m.

The lower shell bed occurs below the gray clayey, sandy, silt and is 2.4 m thick. It is composed of numerous shells in a brown, medium to fine sand matrix. This unit is indicated to be relatively strong by the SPT. The shell bed grades into a gray green, medium to fine sand at 8.6 meters which extends to an elevation of 5 m exhibiting decreasing strength and increasing water content with depth. The gray-green, medium to fine sand reaches a local strength minimum and is saturated at its base.

A sharp grain-size change occurs at this point from the saturated, gray-green medium to fine sand to a dry, greenish-gray, clayey, silty, very-fine sand resulting in a perennial seep. The finer grained unit extends to an elevation of 1.8 m where it contacts a dry, dark gray, silty, very fine sand. The dark gray, silty, very fine sand is prone to spalling along joint surfaces where exposed, especially between the northern end of the Scientists' Cliffs' property and Parker Creek.

Erosion Mechanisms

Site/Subsite: Scientists' Cliffs/Governor's Run

Lower Slope. The lower slopes at Governor's Run fall into two categories. Along most of the shore, small debris fans of upper-slope material have built up to heights of two to five meters and are covered with herbaceous vegetation. Also along these sections, a small sandy beach exists in front of the toe debris. The second lower slope zone coincides with a narrow, low beach approximately 150 m long . Here the toe zone is free of debris and the intact slope is exposed to wave activity during high tides. Along the same part of the shoreline, the cliffs are tall (> 30 m) and seepage erosion has formed a substantial bench along the upper seepage zone (ephemeral seep). The bench is approximately 5 m wide and heavily vegetated. The result is that very little upper slope material is delivered from above the seepage zone to the toe zone. The lack of debris fans along this stretch of cliffs may be apparently attributed to a lack of supply of debris from the upper slope to the slope toe, rather than to greater or more focused wave energy at this location. This is suggested by traces of isolated vegetation in triangular patches that may have become established on debris fans that had accumulated along the toe during bench formation. Once the bench was well-formed, the supply of upper slope debris diminished and the debris fans have been removed except for traces of their uppermost portions. Similar vegetated debris fans are currently present just north and south of the bench cut cliff, where upper slope material is still transported from cliffs of similar height to the toe zone.

Physical and chemical weathering result in disintegration of the clayey, very fine sand which comprises the intact slope material along the stretch where it is exposed. Also, the slope toe is slightly undercut here. This is the only section of the cliffs at this subsite that show evidence of spalling just above the toe.

Most of the toe zone, both to the north and south of this section is covered with either a light mantle of debris forming a laterally continuous wedge shaped deposit or a larger triangular debris fan. Light vegetation has become established on the unconsolidated debris along most of the slope toe.

Midslope. A nearly uniform, fairly gentle incline occurs from the base of the debris fans at the toe to the base of the root zone. A perennial seepage zone occurs at approximately 5 m above the beach where a gray-green medium to fine sand overlies a gray-green clayey, silty, very fine sand. The seepage tends to keep the slope face below moist. Below the seepage zone, the face is covered with a thin veneer of weathered debris which presents a generally uniform planar surface with small rills on its surface. Above the seepage zone is a drier face composed of a gray, clayey, sandy silt which coarsens upward to become a clayey, silty, very fine sand and is prone to fragmental disintegration due to desiccation and other weathering mechanisms. Continuing upslope a seepage zone is encountered where the clayey, silty, very fine sand meets a brown medium sand. Where the topographic surface behind the cliffs is low, this interface is a perennial seep. Where the surface is high, it is an ephemeral seepage zone. Overlying the medium sand is a thick shell bed with a brown medium sand matrix. At this subsite the shell bed is overlain by a one meter thick zone of medium to coarse, orange-brown sand which also exhibits a saturated face where the topographic surface is low.

Upper Slope. The upper slope at Governors Runs tends to be nearly vertical. As of October 1990, there were no slope-top trees on the beach along the entire subsite. However, by summer 1991, an upper slope slump in the upper sand bed had undercut a large tree, which subsequently toppled to the beach carrying a large root ball with it.

Erosion of the upper slope appears to be driven primarily by sapping erosion in a medium sand bed located at an elevation of 18 m. The sand is very loosely consolidated and prone to sapping erosion at its interface with an underlying shell bed. Sapping undercuts the materials lying above, causing them to fail. Material from these failures form fan-type debris piles along the toe zone.

The upper slope bench is located along the 150 m long section of Governors Run with little beach and toe debris. The bench is formed within the upper medium sand that is prone to sapping erosion. The floor of the bench is formed by the less pervious shell bed which underlies the sand sapping zone. The location of the bench at this elevation suggests that the bench was formed by accelerated sapping erosion.

Site/Subsite: Scientists' Cliffs/Scientists' Cliffs North and South

Lower Slope. The entire length of the shoreline along the community of Scientists' Cliffs is partially protected by a beach built up behind evenly spaced groins. Along the southern portion of the shoreline, the slope toe is completely protected by a wide beach and parking lot. To the north, the slope toe is closer to the shoreline, but everywhere along the shore, the slope toe is above all but the highest of water levels. The result is that at most locations toe debris has accumulated and become vegetated with shrubs and trees. In a very few places along the groin-protected shoreline, the waves have removed all of the debris at the slope toe and eroded some intact material. At most places, however, the intact toe material still maintains a relatively gentle slope.

Midslope. Typically, the middle portion of cliffs along the Scientists' Cliffs Community is vegetated. Where exposures are present, a perennial seepage zone is evident where a gray-green, medium to fine sand overlies a gray, clayey, silty, very fine sand. Further upslope is an ephemeral seepage zone where a brown medium sand overlies a gray, clayey, sandy silt. Field inspection of this seepage zone indicates that it is subject to both piping and sapping erosion when the seepage is active. (Piping erosion is similar to sapping erosion in that it is caused by groundwater flow. However, the flow tends to be confined to narrow regions in the cliff face where the erosion creates holes that often resemble pipes). Flow from this seepage zone produces seepage erosion of lower units. Field strength tests indicate the shear strength of the materials comprising the cliffs to be at a minimum at the seepage interface. Sapping and piping erosion undercuts the material above, causing it to slump or fall. In this way, bluff top recession continues despite significant toe protection.

Mid-slope recession below the seepage zone occurs by physical and chemical weathering products being removed by surface wash. Vegetative cover serves to reduce raindrop impact and dry the upper slope surface by interception and evapotranspiration. However, roots of all plants contribute to the degradation of soil fiber by producing acidic conditions around them. Offsetting this effect is the binding action of the roots which forms mats. It is common at Calvert Cliffs for failure to occur along the base of the root mat, causing the mat to slide downslope.

Upper Slope. The bluff top recedes by both seepage undercutting and surface wash of weathered material. Most property owners have removed the tall trees from the cliff edge to prevent loss of root mass and associated soil when trees fall during strong winds.

Site/Subsite: Scientists' Cliffs/ Parkers Creek

Lower Slope. The toe zone is composed of a silty, sandy, clay. The elevation of the toe zone is near mean low water and the toe zone is subjected to nearly continuous wave undercutting which results in spalling of large blocks from the nearly vertical lower slope. Removal of the slope debris is generally quite rapid; only debris from the largest slope failures remains on the beach for periods longer than several weeks to a month.

A partial, ephemeral beach is present along portions of the Parkers Creek subsite. Active deposition and erosion of beach sand has been observed. Near the northern end of this subsite, excavation of the beach uncovered spalled blocks were noted to have been buried by beach depositional processes. Also, at this site, runoff from a heavy thunderstorm ($\approx$1.5 inches in one hour) was observed to erode the top 15 to 20 cm of beach surface along the only portion of this subsite observed to have even a small beach.

Midslope. The active wave undercutting and retreat of the lower slope tends to steepen the midslope sections, which initiates further spalling and shallow sliding in the midslope zone. Typically, spalls work their way up the steep slope face to the perennial seepage zone where the lower sandy shell bed is located. Some spalls are sufficiently large that they extend from beach level to the perennial seep approximately 12 m above the beach. Undercutting and spalling tend to keep the slope face straight and nearly vertical. Above the seep, columnar slope sections separate from the face along tensional fractures and topple or fall to the beach.

Upper Slope. Weathered and leached materials near the bluff top tend to fail in undercut slumps that bury earlier spalled material. Undercut root zones eventually collapse in cantilever type failures.

3.6 Calvert Cliffs State Park

General Site Description (Figures 3.7, 3.8)

The site encompasses the shoreline and cliffs from Rocky Point to 500 meters south of Grays Creek. The subsites are Rocky Point (RP), Grovers Creek North (GVCN), Grovers Creek South (GVCS), and Grays Creek South (GYCS).

The orientation of the cliffs is generally northeast to east-northeast except at Rocky Point where the cliffs face northeast to east. There is no shore protection at this study site. A small beach is present during low tides, but waves frequently reach the cliff base. Offshore sand bars were not evident during an aerial inspection of the CCSP site in October, 1990.

The cliff height at the Rocky Point subsite varies between 15 and 35 meters and slope angles range between 65 and 85 degrees. The cliffs at the Grovers Creek North subsite are substantially lower, ranging between 12 and 18 meters. Here, the slope angle is approximately 60 degrees. Both the Grover Creek South and Grays Creek South subsites have slope angles of 60 degrees with the slope height varying between 15 to 30 meters at GVCS and 15 to 25 meters at GYCS.

The site lies predominantly within the Miocene St. Marys Formation. A small wedge of the highly fossiliferous upper member of the Choptank Formation occurs just above beach level at Rocky Point, but disappears below beach level in the Grays Creek South subsite. The materials composing the slopes of the entire site are interbedded clays, silts, and sands. Some ironstone is present in discontinuous patches up to one meter thick. The stratigraphic units above the water table tend to be highly leached and have a substantially greater fraction of coarse grain sediments than those below the water table.

The surface drainage is quite similar across the CCSP site. Surface water at the site drains toward the cliffs from an area extending approximately 250 meters back from the cliff face. The cliff face is interrupted in three places by perennial streams. One or two groundwater seepage horizons are evident on the cliff face. A major seep occurs between 10 and 15 meters from the cliff top at the contact between a coarse grain sandy unit overlying a gray clay. A smaller volume of seepage is discharged from a thin sandy unit approximately 4 meters below the upper seep.

Geotechnical Properties (Figure 3.9)

The cliffs at Calvert Cliffs State Park range in height from 12 m to 35 m. Five groupings of materials constitute the stratigraphy at this site. A silty sand comprises the portion of the cliff in which soils are developed and which grades into a layer of sand with traces of gravels interbedded with large fractions of silt and clay. Below this, approximately one quarter of the way downslope, the slope material is primarily composed of sand. About halfway down the slope, the materials become predominantly silts and clays which extend below sea-level where they contact a saturated shell bed with a very fine sand matrix.

The elevation at the well-head is 20.0 m. The root zone and soils are developed in a moist, orange-brown, silty, medium sand which is 1.6 m thick. A slightly moist, tan, medium sand containing traces of pea gravel and lenses of stiff white clay occurs at 18.4 m and extends to 16.8 m. A 3.1 m thick, slightly moist, light gray, silty clay with lenses of coarse sand is encountered next followed by a light gray to tan, mottled, fine sand with small amounts of silt and clay, the latter being saturated at about 12.3 m in elevation. The materials continue to be saturated as they change to a dark gray color at 10.6 m. The grain size distribution remains remarkably similar across the color change; however, the material strength declines steadily from the surface down reaching a minimum at the color change.

At 8.4 m in elevation the units change from a dark gray, fine sand to a gray, silty clay with lenses of fine sand. The permeability contrast and saturation of the sand unit create a seepage zone at the base of the dark gray, fine sand. In several places along the cliffs at the Calvert Cliffs State Park site, this seepage zone is responsible for undercutting the weak sand above, resulting in small debris flows and slumps which create benches formed on the more cohesive layer below.

The cohesive, slightly moist, gray, silty clay extends to an elevation of 3.0 m where the material changes to a slightly moist, gray, clayey silt with traces of fine sand. This silt unit is 5.3 m thick and exhibits the highest strength of all of the units in the Calvert Cliffs State Park profile; however, it is strongly jointed and tends to spall in large blocks along joint planes.

During the field description, a dense shell bed was noted to exist below the silt unit at approximately -2.3 m in elevation. It is a cemented, saturated, fossiliferrous layer with a gray sand matrix. The shell bed tends to be more resistant to wave erosion than the underlying strata, and less resistant than the overlying strata. Where these units are exposed near beach level, an undercut nose can develop in the lower slope causing spalling of the silt above.

Erosion Mechanisms

Site/Subsite: Calvert Cliffs State Park/Grays Creek South

<u>Lower Slope</u>. Daily waves and tides are capable of removing all of the unconsolidated debris reaching the toe from the upper portions of the slope. A shell bed in the toe zone is actively being undercut by normal daily wave activity. The bed is densely fossiliferrous and the matrix surrounding the shells is a medium sand cemented with calcium carbonate. The shell bed dips below mean high tide at the GRAYS Creek site and is exposed above water level along approximately 200 m of shoreline. Above the shell zone, the lower slope fails by surficial erosion of weathered material by groundwater seepage and direct precipitation.

<u>Midslope</u>. Above the shell bed and above the beach where the shell bed is below tide, the slope maintains a relatively smooth, straight profile to the base of the root zone near the bluff top despite the existence of two sapping

zones and two major changes in material composition. An 11 m thick sequence of clayey silts and silty clays extends from beach level to a contact with a unit of fine sand at which a permanent seep occurs. The mid-slope units are eroded in nearly equal proportions by two processes, surficial removal of weathered material and sheet spalling.

Physical and chemical weathering reduce the outer few centimeters of the slope face to a loose veneer which is removed by surface wash during rain storms. During rainfall, the weathered surficial material may become a viscous slurry and flow slowly down the slope. Material which doesn't reach the toe dries on the slope face until the next rain.

In addition to surface wash, the exposed surface material spalls in thin sheets along planes sub-parallel to the slope face. Spalling surfaces are ubiquitous in materials with high proportions of silt. Large spalls are uncommon at this subsite with the single exception of a large, blocky spalling event just south of the mouth of Grays Creek. Here, the toe zone shell bed was sufficiently undercut to cause a 5 m tall X 5 m wide X 1-2 m thick block to fail along a slope-parallel tension crack in Spring, 1991. Observers noted the widening of the tensional crack over a period of several weeks prior to the collapse. Since the collapse, the less consolidated material above the spalling cavity has slumped onto and buried the spalled blocks creating a fan like structure in the toe zone. Currently, such large block spalling is an anomalous condition along this slope. It is worth noting, however, that the large spall occurred along the section of slope undergoing the most severe undercutting.

Midway up the silt-clay sequence are two thin layers of fine sand separated by a massive silt layer. The sand layers are each 15 to 30 cm thick and the separating massive silt ranges between 20 and 40 cm in thickness. The sands are saturated and experience sapping erosion at the cliff face. The sapping zones are expressed on the cliff face as two horizontal gaps and are laterally continuous along the entire extent of this subsite. While their undercutting effects are minimal, they are capable of supplying a nearly continuous supply of water to the lower slope face. The moisture tends to accelerate physical and chemical weathering and may promote the weakening of near surface spalling faces.

Upper Slope. Overlying the 11 m thick silt-clay strata is a 6 m thick sequence of predominantly fine sand overlain by a 4 m thick sequence of silts and clays which become progressively more fine-grained until the root zone is encountered approximately 2 m below the bluff top. The fine-grained units near the surface are dissected in places by drainage channels and do not form a continuous horizontal barrier to infiltrating water. However, they tend to retard the rate at which the groundwater can move into the sandy units below. Hence, intense piping of groundwater at the sand/silt-clay interface tends to be less common than sapping. A permanent seep exists at the base of the sand unit at an elevation of 8-11 m.

A rare deep-seated rotational slump is apparent at the south end of Grays Creek South slopes. The rotational failure surface originated in the saturated zone at the sand/silt-clay interface. The failure is intimately associated with a 0.5 - 1 m thick lense of ironstone formed within the saturated lower portion of the fine sand unit. The majority of the ironstone now rests as a debris pile resulting from a collapse of the layer. No witnesses have described the actual failure, but the configuration of a small remaining block of ironstone on the current slope indicates that the silts below were eroded by sapping and surficial erosion of weathered material, leaving the ironstone to form a cantilever support for the relatively independent slope above. The ironstone overhang eventually collapsed, truncating the toe of the upper slope and reducing its ability to maintain rotational equilibrium.

Site/Subsite: Calvert Cliffs State Park/Grover Creek South

The stratigraphy of this subsite is almost identical to that of Grays Creek South. Hydrologically, the seepage zones are in the same positions relative to the stratigraphy but, somewhat less water may be present because of a smaller surface collection area at the ground surface.

Lower Slope. Stratigraphically, the slope toe is entirely occupied by the shell bed described in the toe zone of the north end of the Grays Creek South subsite. However, debris from slope activity above has completely covered the slope toe. Above the beach level debris fans, the intact silt-clay formations are exposed and their faces stand at steeper angles than the faces at Grays Creek South. The silt-clay exposures show evidence of numerous spalling events. It is likely that the tide level shell bed was eroded from beneath the silt-clay formations causing the silt-clay faces to be undercut and spall. Such a process is actively occurring at the north end of the Grays Creek South subsite and is described above.

Midslope. Where the intact face is exposed, the slopes here tend to be steeper that those of the Grays Creek South site. Spalling is more common and the individual events larger. This is principally due to the oversteepening of the slope below translating up slope - the steeper the slope, the greater the tensile stress on spalling faces, and the more frequent and larger the spalls.

In addition to spalling, physical and chemical weathering reduce the outer few centimeters of the slope face to a loose veneer which is removed by surface wash during rain storms. During rainfall, the weathered surficial material may become a viscous slurry and flow slowly down the slope. Material which doesn't reach the toe dries on the slope face until the next rain.

Seepage and sapping erosion occurs at the same stratigraphic locations as at the Grays Creek South subsite, but all seeps seem to be slightly less active than those at Grays Creek South.

Upper Slope. As the oversteepening proceeds upslope it undercuts the leached and less coherent materials of the unsaturated zone. These materials slump when undercut, building a fan-like pile at the toe on top of the blocky debris previously spalled from the slope. The top two meters of the slope tend to stand in vertical faces or form overhangs due to the binding effect of tree roots. It is evident that the undermining of the bluff top has occurred rather rapidly. Trees and vegetative mats that have fallen from the bluff top are still alive indicating that their roots have not been exposed long enough to kill the plants. It should be noted here that there are many more downed trees on the beach along this section of slope than at the Grays Creek South subsite.

Site/Subsite: Calvert Cliffs State Park/Grover Creek North to Rocky Point

Induration is the key difference between the slopes at Rocky Point and the other slopes of the Calvert Cliffs State Park Site. Induration is apparent in all seepage zones. Laterally continuous, horizontally bedded ironstone formations form sheets of high shear strength which increase in thickness and number moving north from Grover Creek to Rocky Point. These sheets reinforce the slope and prevent major slumps or rotational events. However, surface runoff and sapping erosion carry sizeable quantities of unconsolidated material to debris fans at the base of the slopes.

Lower Slope. Stratigraphically, the toe zone is entirely occupied by the shell bed described in the toe zone of the north end of the Grays Creek South subsite. However, debris from slope activity above has largely covered the slope toe. Between the narrow triangular tops of the debris fans the face of the shell bed is evident and it exhibits a nearly vertical or, in some locations, a slightly concave profile.

Midslope. Immediately overlying the shell bed is an indurated sheet of ironstone nearly one meter thick and laterally very extensive. The shell bed below is eroded to the degree that the ironstone is cantilevered in many places and large rectangular fragments of ironstone litter the beach. From the bases of the debris fans on the beach to the base of the root zone near the bluff top, the slopes exhibit a regular inclined profile which is less steep that the profile at the Grover Creek South subsite and nearly equivalent to the incline of the profile at the Grays Creek South subsite.

Spalling is not as frequent along these slopes as at Grover Creek South and tends to occur in thin sheets. In addition to spalling, physical and chemical weathering reduce the outer few centimeters of the slope face to a loose veneer which is removed by surface wash during rain storms. During rainfall, the weathered surficial material may become a viscous slurry and flow slowly down the slope. Material which doesn't reach the toe dries on the slope face until the next rain.

Seepage occurs above the ironstone horizons and produces sapping erosion, particularly near the top of the silt-clay unit. Within the overlying sand horizons, the thickness and induration of the ironstone decreases with increasing elevation. These ironstone layers do lend some stability to the upper unsaturated zone, which is very tall in places. Virtually no slumping of the unsaturated zone is evident, in contrast with the slumped unsaturated horizons at Grover Creek South and at the Chesapeake Ranch Estate's Laramie Lane subsite.

Physical and chemical weathering of the slope surface combine with seepage and storm runoff to erode material from the slope and deliver it to the debris fans below. Large gullies extending the entire length of the slope are common at this subsite. The gullies tend to terminate on ironstone sheets especially where the sheets are cantilevered over the slope below.

Upper Slope. The bluff top is nearly vertical where bound together by tree roots. Virtually no trees are found on the beach along this section. indicating a relatively stable bluff top.

3.7 Chesapeake Ranch Estates

General Site Description (Figure 3.10, 3.11)

The site encompasses the shoreline and cliffs from Cove Point Hollow to Seahorse Beach. The subsites are Cove Point Hollow (CPH), Little Cove Point (LCP), Laramie Lane (LL), Driftwood Beach South (DBS), and Seahorse Beach North (SBN).

The cliff orientation ranges from east-northeast at the Cove Point Hollow subsite to southeast at Seahorse Beach North. The shoreline along the cliffs is unprotected except for a few groins at Driftwood Beach and Seahorse Beach, where no cliffs are present. A small beach is present during most tidal conditions along the entire site, except at the locations where slide debris extends to the low tide line. One notable exception is at the Little Cove Point subsite, where the cliff face extends into the water. One or two shore-parallel sand bars are found along most of the site.

North of Little Cove Point, cliff height ranges from 10 to 25 meters and the slope angles are shallow to moderate ranging between 30 and 50 degrees. Cliff heights at the Little Cove Point subsite range between 16 and 22 meters and the slopes are steep, varying between 70 and 85 degrees. The slopes at the Laramie Lane subsite are distinctly different from those to the north or south. They range in height from 15 to 35 meters and are characterized by steep, nearly vertical bases, more gentle mid-slopes (40-60 degrees), and a nearly vertical bluff top. Three large recent slides have occurred in the upper materials at the Chesapeake Ranch Estates. The slide debris has accumulated at the slope toe giving the entire slope a moderate, nearly uniform profile at an inclination of approximately 65 degrees. The debris is being gradually removed by wave action over a period of one to three years. The slopes at the Driftwood Beach South subsite are 16 to 22 meters high and have slope angles of 60 to 80 degrees. At the Seahorse Beach North subsite the slopes are 12 to 30 meters high and are inclined at angles of 65 to 85 degrees.

The site lies entirely within the Miocene St. Marys Formation. There is some question as to the age of the top 15 meters of coarse grained sediments. For our purpose, it is sufficient to note that the material properties of the upper 15 meters is distinctly different from the lower 15 meters of cliff. The lower portion of cliff is comprised of interbedded fossiliferous sands, silts, and clays. The upper 15 meters is composed of coarse grained sands with some pebbles and gravels and has very different geotechnical properties than the lower materials. Ironstone is present in laterally discontinuous patches up to one meter thick.

From the Cove Point Hollow subsite to the Laramie Lane subsite, surface drainage originates from as far as 700 meters from the cliff face. Along the Driftwood Beach South subsite, drainage towards the cliffs extends 350 meters from the cliff face. Surface drainage at the Seahorse Beach North subsite is essentially that of a hilltop. Groundwater seepage is generally very active at the base of the coarse grained sands of the upper cliff sections. It is particularly strong where topographic lows intersect the cliff face.

Geotechnical Properties (Figure 3.12)

The cliffs at Chesapeake Ranch Estates range in height from 10 m to 35 m. The slope materials can be divided into five major groups. The soil horizons and root zone are developed in a sandy material. Below the soil and root zone is a thick, highly weathered, medium to coarse sand with traces of pea gravels and thin clay laminations. This unit is moist throughout and is saturated at its base. A seepage zone occurs where the sand unit overlies a series of interbedded sands and clays. About half way down the slope, the interbedded sands and clays give way to a distinct massively bedded fine sand with a significant silt fraction. This bed is nearly 6 meters thick and grades into a gray, clayey silt which extends below beach level.

The ground surface at the well site is at an elevation of 29.5 m. The stratigraphic unit containing the soil horizons and root zone is approximately two meters thick and is composed of a moist, brown, silty, clayey sand. Immediately below, at an elevation of 27.4 m, lies an extensive sand zone which is highly weathered and is subject to iron staining; the color varying from tan to yellow to orange. A strength minimum occurs near the top of this unit and a maximum near the base. Thin lenses of pea gravel and clay laminations are present but discontinuous in this unit. The sands are nearly 12 meters thick and are highly porous and permeable resulting in a perennial seepage zone where they meet a series of interbedded clays and sands at an elevation of 15.6 m. The clay units range in thickness from centimeters to nearly a meter. The interbedded sands are of similar thicknesses and tend to be thin seepage zones. The saturated sands and clays of this unit are very weak and for the likely failure surface for the large slides observed in this section of the cliffs.

The top of the gray, fine sand unit just beneath the interbedded sands and clays occurs at an elevation of 14.1 m. About 30 percent of the material in this unit is finer than very fine sand resulting in a dense, massive texture. The SPT indicates that it is moderately strong. A series of thin shell beds occur near the base of this unit and exhibit a slight increase in the strength of the unit. Two permanent seeps occur in shell beds, each with a matrix of medium sized sand. Below the shell beds, at an elevation of 6.2 m is a bed of moist, gray, clayey silt which also appears to be massive and dense. However, the SPT indicates that the unit has a low to moderate strength.

Erosion Mechanisms

Site/Subsite:Chesapeake Ranch Estates/Seahorse Beach North

Lower Slope. Physical and chemical weathering of exposed surface material reduces cohesion and causes fragmental disintegration. Gravity and surface runoff transport the loosened material downslope creating a wedge-shaped mantle that thickens toward the toe.

Daily waves and tides and storm runoff are capable of removing most of the unconsolidated debris generated by slopes 20 m or less in height. Taller slopes may have accumulations of upper slope debris at the toe. Intense wave action due to strong onshore winds and/or high tides removes large volumes of toe debris and may undercut intact slope material; however, vertical slopes or overhangs indicative of intense undercutting are not observed at this site.

Midslope. A strong perennial seep occurs at about 5 m above the toe from Seahorse beach to Driftwood beach. The seepage zone marks the transition between a lower gray silty clayey very fine sand and an overlying thin interval of interbedded medium sands and clays. The sands of the interbedded unit are continuously saturated, which maintains the clays in a moist, plastic state. In addition, the sands are prone to piping and sapping which removes the sand from the between the clays creating gaps which, eventually collapse. In the taller cliffs (> 25 m), the weight of the overburden is sufficient to cause failure within the saturated clays and a sliding surface is produced along the clay/sand beds. It is likely that the saturated sands contribute additional water to the already weakened surface and the failure propagates along the clay/sand bed. Spherical scarps are evident with nearly vertical upper faces indicating that the failure is rotational in nature.

Along sections without a recent rotational failure, a break in the slope profile typically occurs at the perennial seep. The underlying saturated very fine sand offers more resistance to surficial erosion and stands at a steeper angle than the looser interbedded sands above. Water from overlying seepage zones exits the slope face at sapping or piping zones and undercuts the overlying material, transporting sediment and debris down the slope face to the slope toe via gullies. Gullies on faces subject to piping originate in the middle of the slope and widen downward. Stormwater runoff also washes over the entire slope face carrying weathered, loose debris to the slope toe.

Upper Slope. The upper strata tend to be highly leached and weathered. The mid-slope rotational slides either simultaneously carry into the upper slope materials or undercut them to such an extent that subsequent bluff top failures are inevitable. The roots of trees and shrubs tend to bind the upper 1-2 m into a mass that frequently either over hangs the upper slope or results in a vertical face at the bluff top. Retreat of the bluff top occurs when undercut trees and portions of root mass eventually fall, along with spherical masses of soil.

Site/Subsite: Chesapeake Ranch Estates/Driftwood Beach North to Laramie Lane

Lower Slope. Physical and chemical weathering of exposed surface material reduces cohesion and causes fragmental disintegration. Gravity and surface runoff transports the loosened material downslope creating wedge shaped debris fans that thickens toward the toe.

Daily waves and tides and non-catastrophic storm runoff are capable of removing most of the unconsolidated debris generated by slopes 20 m or less in height. Taller slopes have accumulations of upper slope debris at the toe. Intense wave action due to strong onshore winds and/or high tides removes large volumes of toe debris and may undercut intact slope material. Here, in contrast to Seahorse Beach North, the toe debris seems to be more vigorously removed by daily waves, tides, and storm run-off. Spalling of blocks of the clayey silt in the toe zone is common and continuous. The spalling process is accelerated by groundwater leaching along nearly vertical tension planes which are weakened and act as fracture surfaces for spalling events. Here, spalling at the base of the perennially saturated clayey silt of the toe zone actively undercuts the remainder of the lower slope, forming nose-like profiles at the interface with the sandier unit above and vertical to concave faces in the clayey silt below. The permeability contrast at this interface creates a perennial seep along which sapping erosion occurs forming thin, concave gaps where the sands have been removed.

A difference in the materials composing the toe zone is postulated to be the reason that spalling is more active north of Driftwood Beach than north of Seahorse Beach. Field observations indicate that the toe zone strata are finer grained north of Driftwood Beach than the equivalent material north of Seahorse Beach. It should be noted, however, that a greater magnitude of wave undercutting could also be responsible for more active spalling at that site. Therefore, it is imperative that the wave climate at the Chesapeake Ranch Estate site be evaluated under a variety of wind, wave, and tidal conditions.

Midslope. A strong perennial seep occurs at about 5 to 6 m elevation along the cliffs from Driftwood Beach to the area of shoreline lying just east of Laramie Lane. The seepage zone marks the boundary between a gray clayey silt and an overlying unit containing several fining upwards cycles of shell fragments in a matrix composed of fine sand at the base of each cycle and fining to a silt at the top of each cycle. At the seepage interface, thin horizontal trenches are formed by sapping erosion. The cyclic shell sequence is lightly cemented and is relatively strong, as indicated by field shear strength tests. The strength and cementation of this unit causes it to form nose like projections in profile.

Above the cyclic shell beds is the same gray, silty, clayey, very fine sand found in the toe zone just north of Seahorse Beach. Like the Seahorse Beach location, this unit does not spall, but is covered by a thin veneer of weathered fragmental material. It is also prone to gullying by surface wash. At 15 m above the beach, the gray, silty, clayey, very fine sand grades into the layer of interbedded, saturated medium sands and clays previously discussed for Seahorse Beach location. As at Seahorse beach, a minimum shear strength is indicated in the SPT tests for the seepage zone perched on the interbedded sands and clays. Where the overburden above the interbedded sands and clays is sufficiently large (>25m), the saturated clays, weakened by sapping erosion, fail in rotational failures. Spherical scarps are evident with nearly vertical upper faces indicating that the failure is rotational in nature.

Several sandy zones of varying permeability can occur above the interbedded sand/clay zone. The exact number of zones on any slope face varies with the cliff height. Each of the permeability contrasts creates a perched water table. At locations without a recent deep-seated slide, the seepage flow exits the slope face at sapping or piping zones, undercuts portions of the slope above, and transports sediment and debris down the slope face to the slope toe via gullies. Gullies on faces subject to piping originate at the permeability contrast and widen downward. Stormwater runoff also washes over the entire slope face carrying weathered, loose debris to the slope toe.

Upper Slope. The upper strata are composed of medium to coarse sands with lenses of pebbles and cobbles and tend to be highly leached and weathered. The mid-slope rotational slides either simultaneously carry into the upper slope materials or undercut them to such an extent that subsequent bluff top failures are inevitable. The roots of trees and shrubs tend to bind the upper 1-2 m into a mass that frequently either over hangs the upper slope or results in a vertical face at the bluff top. Retreat of the bluff top occurs when undercut trees and portions of root mass eventually fall, along with spherical masses of soil.

Site/Subsite: Chesapeake Ranch Estates/Little Cove Point

Lower Slope. Physical and chemical weathering of exposed surface material reduces cohesion and causes disintegration. Gravity and storm runoff transports the loosened material downslope creating a thin, patchy mantle of surficial debris on the slope toe. The geometry of the toe zone at Little Cove Point and north stands in striking contrast to the toe zones of the slopes to the south of Little Cove Point. Here the toe is gently inclined away from the beach crest at a shallow angle. It is apparent that waves are still able to remove the veneer of surface debris from the toe just above beach level, but undercutting and spalling due to wave action in the toe zone are non-existent. The material comprising the toe zone from south of Little Cove Point to north of Little Cove Point is a clayey silt composition varies little along this length of cliff. Apparently, the wave energy striking the northeast facing slopes of Little Cove Point is substantially less than that striking the southeast facing slopes.

A seepage zone exists approximately 5 m above the beach and at this interface sapping erosion truncates the gently inclined profile of the more permeable unit above by removing intact slope material and undermining the gullied slope above.

Midslope. Slumping and spalling are minimal north of Little Cove Point. The material comprising the upper slopes north of Little Cove Point is stronger and partially cemented in places. Ironstone formations are common. Slope erosion occurs principally through chemical and physical weathering and erosion by seepage and surface runoff. Field inspection indicates that the seepage discharge north of Little Cove Point is significantly smaller than that observed along the slopes from Driftwood Beach to Laramie Lane. Large gullies are present on most of the slopes. An upper intermittent seepage zone also exhibits evidence of sapping erosion and is responsible for creating significant overhangs above.

Upper Slope. The roots of trees and shrubs tend to bind the upper 1-2 m into a mass that frequently either over hangs the upper slope or results in a vertical face at the bluff top. Retreat of the bluff top occurs when undercut trees and portions of root mass eventually fall, along with spherical masses of soil.

4. Mechanisms and controls of coastal slope failure

4.1 Wave undercutting and its relation to other controlling factors of coastal slope erosion.

Undercutting by wave activity, whether currently active or not, is common to all our study sites. It is this undercutting that initiates and, to some extent, maintains the slope erosion. The rate of undercutting depends on the orientation of the shoreline, the offshore bathymetry, the elevation of the slope toe, the presence of slope toe protection (e.g. bulkhead, beach), and the material properties.

In all cases we examine, wave undercutting is a basic environmental factor. In some cases, particularly where the undercutting rate is very rapid, undercutting is the dominant environmental factor driving the erosion mechanisms and rates for the entire slope. In other cases, however, including most of the slopes we examine, undercutting is only one of several environmental factors controlling the rate of slope erosion. This is particularly true for the middle and upper portions of the slopes, for which the recession rate is often more rapid than, and therefore relatively independent of, the wave-driven recession of the lower slope. When recession of the middle and upper portions of the slopes occurs more rapidly than recession of the lower slopes, a characteristic slope profile is formed in which the middle portion of the slope is more gentle (has receded back from) the steeper lower slope. In these cases, the mechanisms of slope erosion occurring on the middle slopes and, therefore, the factors controlling that erosion, are not a direct function of the lower slope erosion. Wave action is needed to initiate slope erosion and to remove the debris shed from the slope, but the mechanisms and rates of erosion of the middle and upper slopes are controlled by local surface water and groundwater, slope geometry, and material strength, and not by toe undercutting. An extreme case of this occurs at the NRL site, where complete protection of the slope toe has been in place for 45 years. Erosion of the middle and upper slopes continues even after this long period of toe protection. The types of erosion and the environmental factors controlling the future recession rates and ultimate stable form of the NRL slope are independent of undercutting at the slope base.

4.2 Groups of slope erosion mechanisms: Classification of the Calvert Cliffs slopes

The erosion mechanisms operating along the Calvert Cliffs are varied and complex. Most mechanisms operate to some degree on all of the bare, eroding slopes, and more than one erosion mechanism generally contributes significantly to the observed slope form and slope recession at any one site. A major part of CCSEP involves identifying the dominant slope erosion mechanisms at each site and determining the critical values of environmental factors controlling the dominant types of erosion and their rates. It is this information that is necessary for determining the response of the slopes to change in external factors, such as sea level rise.

The complexity of the slope erosion is augmented by the fact that the types of erosion processes acting on any individual slope may not be constant in time. Rather, a cyclic variation may exist wherein a period of direct toe undercutting, slope oversteepening, and active, deeper slope erosion is followed by a period during which the slope debris protects the slope toe from erosion and surficial erosion processes cause the slope to become gentler. The cycle begins again when the slope debris is removed from the slope base and erosion of the intact toe resumes. Such cyclicity has been observed on other coastal cliffs (e.g. Edil and Vallejo, 1977; Quigley et al., 1977) and may also operate along portions of the Calvert Cliffs.

As an attempt to bring some order to this complex situation, we propose a system for classifying the Calvert Cliffs according to their geometry and the relative rates of the dominant erosion processes. The goal of this classification is identification of the dominant erosion processes from readily observable slope features. The classification system also provides a conceptual basis for further investigation and application regarding:

(1) development of field experiments with which we will attempt to isolate critical values of environmental factors that determine the erosion type and rate and the transition between dominance of one erosion mechanism and another;

(2) prediction of the range of possible erosion processes and their rates in response to sea level changes;

(3) a technical basis for developing and evaluating erosion mitigation projects.

Our classification system is based on three factors: (1) a distinct difference in material saturation and erosion resistance typically exists between lower and middle sections of individual slopes, (2) the range of erosion mechanisms that dominate the recession of lower and midslope sections are often different, and (3) the resulting slope geometry of lower and midslopes is often considerably different.

The material difference is based on the common presence of a strong permeability contrast occurring typically within 5 to 15 m of the slope toe. Materials immediately overlying the permeability boundary are typically porous, granular in structure, and saturated, forming a zone of groundwater seepage that is either permanent or continuous during most of the year. The material below the permeability contrast is much less permeable, generally darker in color, and massive in structure. The lower materials tend to be more resistant to surficial erosion processes related to wetting and drying, freeze/thaw, and surface wash from direct precipitation or groundwater seepage. Often, failure of the lower slope materials occurs through spalling and falling of slope segments oversteepened by direct wave activity. In some cases, the midslope materials overlying the permeability contrast also fail by spalling or shallow sliding on a wave oversteepened slope, but more commonly, the midslopes fail by hydrologically driven processes related to surficial erosion of weathered material by direct precipitation or groundwater seepage, or by deep-seated failures along weak strata experiencing high groundwater pore pressures.

Different slope geometries result from the different properties and typical groups of erosion mechanisms in the lower and midslopes. In most locations along the Calvert Cliffs, the rate of midslope recession appears to be more rapid than lower slope recession and the midslopes are observed to retreat back from the lower slopes. In this case, one of several common slope forms are produced, all of which have a more gently inclined midslope than lower slope. When the rate of lower slope recession becomes even smaller relative to the midslope recession rate, the entire slope may erode to a gentler angle characteristic of midslope surficial erosion. In this case, the waves serve primarily to remove the slope debris and perform only a small amount of direct undercutting of intact material. Where toe protection is complete, waves cannot remove even the slope debris accumulated at the toe. Because a colluvial debris fan builds at the slope toe, these slopes develop a profile of increasing slope angle with elevation. In the other extreme case, where the lower slope recession proceeds more rapidly than the rate at which either surficial or deep-seated slope failures erode the midslope, the entire slope becomes very steep and the midslope fails primarily by shallow sliding or spalling.

The classification system contains four basic classes of slopes, organized according to the relative recession rates of the slope base Rb and midslope Rm. Figure 4.1 presents schematic slope profiles and summarizes the classification scheme.

Type I Rb = 0. Type I slopes no longer experience toe erosion. Debris eroded from the slope accumulates and builds a gently inclined mantle up from the slope toe. A typical lower slope angle for Type I slopes is approximately 35 degrees. The debris fan may terminate in the midslope section, in which case a three part slope is formed, with the slope angle increasing with elevation. After an extended period of time, the debris fan may entirely cover the midslope and a two-part slope (fan/upper slope) exists.

Generally, undercutting by ephemeral seepage, surficial erosion by overland flow, and columnar toppling account for the retreat of the upper slope. Upper slopes tend to be quite steep, ranging from 55 degrees to vertical. Three of our study sites, NRLN, NRLS, SCS, have sufficient protection to prevent further toe erosion. These sites allow us to observe the manner in which the toe and mid-slope regions build as the bluff top continues to recede.

Type II Rb << Rm. Type II slopes are slopes where waves can remove most slope debris from the base and may occasionally erode some intact toe material, but at a rate slower than the hydrologically dominated erosion processes operate on the lower slope. Sapping, piping, solifluction, and overland flow tend to dominate from near the base of the root zone to the slope toe. The intact material near the slope toe will exhibit slope angles that are very similar to those of the mid-slope. Slopes with relatively homogeneous materials throughout will exhibit a straight profile from the toe to the bluff top. Slopes with materials of contrasting geotechnical properties at different elevations will show slope breaks at material transitions, although the variation in slope angle will be smaller than the contrast found between the lower slope and midslope typical of the more common Type III slopes. The range of angles for Type II slopes for a line drawn from slope toe to bluff top is 40 to 52 degrees. The angle of slope segments of Type II slopes fall within a range of 35 to 65 degrees. The subsites at Little Cove Point and Scientists' Cliffs North fall into Type II. Classification of a slope as Type II is made on the profile of the intact slope material. For example, Grays Creek South (Figure 3.8) has a relatively straight profile, which is a characteristic of some type II slopes. However, the survey included a temporary debris pile at the slope toe creating a profile with a shallow toe zone angle. Since the survey, the toe debris has been eroded and the toe zone of Grays Creek South is nearly vertical.

Type (III) Rb < Rm. Type III slopes are the most common along the Calvert Cliffs. On these slopes, waves erode the lower slope at rates sufficiently fast to cause spalling or falling of lower slope material. At the same time, hydrologically driven processes in the midslope operate rapidly enough to cause the midslope to recede back from the lower slope. The result is a slope that displays a distinct break in the slope angle at the permeability contrast separating the lower and midslopes. The lower portions of Type III slopes have angles between 75 and 90 degrees, whereas the midslope angles generally fall between 35 and 65 degrees. Different hydrologic conditions and midslope erosion mechanisms produce different midslope profiles. Groundwater piping will create gullies which have their heads at the pipe exit, whereas more laterally continuous groundwater sapping produces a more uniform erosion of the slope below, resulting in a smooth, planar midslope. Type III slopes include Holiday Beach, Governors Run, and Grays Creek South.

Type IV Rb ≈ Rm. In these slopes, wave undercutting is sufficiently rapid that the recession rate of the lower slope is greater than the rate at which hydrologically driven processes cause the midslope to erode. The midslope becomes oversteepened and both lower and midslope erosion is driven by spalling and shallow sliding at a rate determined directly by the rate of wave-driven undercutting. Relatively steep, straight slopes form at slope angles of 70 degrees or more if the materials are relatively homogeneous. However, where vertical geotechnical contrasts exist, each slope segment will fail at an angle characteristic of the material in each zone, resulting in a segmented, steep slope profile. A potential for deep-seated slope failure exists in some Type IV slopes. This occurs where a soft clay layer occurs within the saturated seepage zone at the lower/midslope boundary, and a sufficient thickness of porous and permeable slope exists above the seepage zone, producing elevated pore pressures and high shear stresses within the soft clay. The result is a rotational scarp extending upward through the unsaturated zone to near the bluff top. The debris resulting from the slide accumulates at the toe in wedges that are removed by subsequent wave action. Type IV slopes are characterized by an overall slope angle that is steeper than any other type of slope. Type IV cliffs are found at the Randle Cliffs, Parker Creek, and Laramie Lane subsites.

It is worth emphasizing that the classification system is based on *relative* erosion rates of the lower and midslope. Although all Type IV slopes experience significant toe undercutting, all Type IV sites do not necessarily experience greater wave energies, or have greater undercutting rates, than other slope types. For example, a Type III slope might experience large lower slope recession rates, but would be classified as a Type III slope if the midslope recession rate exceeds that of the lower slope. The slope measurements we have made to date indicate that the slope angles characteristic of the four basic slope types fall into distinct, non-overlapping groups. These angles are measured from the bluff top to the intact material at the slope toe. Table 3 presents the slope angles typical of each type.

Table 3. Summary of slope types

Slope type	Bluff top to toe range (degrees)
Type I	32 to 40
Type II	40 to 52
Type III	52 to 65
Type IV	65 to >90

This is a potentially important and useful result. Our slope classification is based on observations of groups of erosion processes and rates that typically occur together, and on the slope geometry developed by these groups of processes If the type of slope and, therefore, the typical group of erosion processes, can be determined based on the overall slope angle, the classification of individual slopes can be done quite readily. Once classified into a particular type, the erosion mechanisms acting on that slope, and the environmental factors controlling that erosion, are known. Classifying slope type by angle can also provide the opportunity to make classifications from aerial photographs or detailed maps. In the next phase of CCSEP, we will be conducting surveys of additional slopes to test this potential simplification of our classification system.

4.3 Environmental factors controlling the recession of each slope type.

Environmental factors control the rate at which different erosional mechanisms act and, therefore, determine the dominant erosion mechanisms occurring at each location. For instance, low wave energies might be capable of very little erosion, allowing a colluvial fan to develop along the lower slope. In this case, slope erosion and recession rates are predominantly determined by hydrologic and material properties intrinsic to the slope itself. At a similar site, a much larger amount of wave energy would be capable of cutting into intact material, causing spalling and shallow sliding that would be far more rapid than any other erosion mechanism, thereby directly driving the recession of the entire slope. Identification of critical values of environmental factors controlling erosion (in this example, the level of wave energy) is central to a quantitative approach to predicting the slope response to changes in external variables, such as a sea level rise.

Type I Rb = 0. Toe protection has been implemented for decades for the Type I slopes of this study. Wave erosion at the toe has been halted, resulting in the accumulation of debris eroded from the slopes above.

Above the debris fan, slopes attain angles characteristic of hydrologically dominated erosion. The rate at which this erosion takes place depends on the amount of water available to the slope surface. Heavy rain from large convective storms or hurricanes will create surface wash which removes weakened and weathered surface material. Erosion due to the seepage of groundwater may result from long duration precipitation events or it may occur where there is a very large groundwater recharge area, so that seepage occurs over extended time periods. A contrast in permeability between adjacent slope materials is also necessary to produce seepage discharge at rates sufficient to cause erosion.

Bluff tops are typically bound by root strength and retreat is controlled by undercutting due to seepage or overland flow surficial erosion.

Type II $Rb << Rm$. Wave action is capable of removing eroded debris, but hydrologic processes dominate the recession of type II slopes. Two factors may control the response of the lower slopes. First, the wave climate over time may be sufficient to remove the debris delivered to the slope toe from above, but not capable of great amounts of additional erosion. Secondly, the material comprising the slope toe may be strong enough to resist significant erosion by the waves - a rock slope would be an extreme case. An increase in toe erosion rate, which might cause a Type II slope to become a Type III slope could be driven by and increase in water level, an increase in wave height, or an increase in the frequency of wave events.

Below the perennial seepage zone, the rate of erosion is controlled by the amount of water which flows over the slope surface. The source of the water may be from surface wash or groundwater seepage. Above the perennial seep, in addition to overland flow, seepage erosion is capable of undercutting the overlying strata causing oversteepening and collapse. Groundwater flow and material properties control undercutting rates, while overland flow, slope angle, and material properties control surface erosion. A change in the rate of midslope erosion is most likely to be caused by an increase in the groundwater seepage rate or duration. Bluff top recession is controlled by the rate of erosion below the root zone and the extent of its capacity to resist cantilever type failures.

Type III $Rb < Rm$. In the toe zone, wave undercutting removes all debris delivered from upslope and actively erodes intact slope material. Midslope erosion type and rate depend on the configuration of the seepage discharge, quantity of seepage discharge relative to surface wash; erodibility of slope surface. An increase in the toe erosion rate could cause a Type III slope to change to a Type IV slope. That is, an increase in the wave energy could increase the rate of lower slope erosion by spalling and shallow sliding. The spalling and shallow sliding in the lower slope would, in turn, oversteepen the midslope causing shallow sliding there at a rate which exceeds the rate of erosion by hydrologic processes. In this way, the slope would become steeper and dominated by spalling and shallow sliding as it changed from Type III to Type IV.

Type IV $Rb \approx Rm$. The recession rate of lower slope is driven by wave erosion and is greater than hydrologically dominated erosion rates typical of midslopes. Therefore, the midslope responds to oversteepening from below by spalling or shallow sliding. The rate of erosion due to sliding or spalling depends on the degree of saturation and the strength and composition of the near surface materials. Occurrence of deep-seated failure depends on the height of upper slope; pore pressures at failure zone; strength of material at failure zone

4.4 Field Experiments

Criterion Three of the site selection criteria was used to narrow the list of potential sites to those that provided the best conditions for isolating and identifying critical values of the environmental factors that control the types and rates of slope erosion. That criterion was: The properties of individual sites must permit between-site comparisons in which a large variation in one factor observed along with only minor variation in all of the other controlling factors. Each such comparison comprises a field experiment that will help us define the critical values of the environmental factors controlling slope instability along the Calvert Cliffs.

The following discussion and Table 2 describes the field experiments we have identified.

Material Strength

Large slope failures usually occur in materials that are relatively weak. Smaller failures and surficial erosion occur in all materials but at different rates which are largely determined by material strength. The strength of a material is determined by characteristics such as grain size, moisture content, cohesion, and internal friction. Slopes having similar shoreline features, undercutting rates, and slope heights, but different material properties will be compared to determine the role of material strength in slope erosion at Calvert Cliffs. Critical values of material strength and pore pressures in weak horizons will be identified to provide a working model of slope failure at these sites. Comparisons will be made between the following subsites:

Randle Cliffs vs. Holiday Beach
Parkers Creek South vs. Governors Run
Rocky Point vs. Grays Creek South
Little Cove Point vs. Driftwood Beach South
Holiday Beach vs. Parkers Creek South
Holiday Beach vs. Cove Point Hollow
Parkers Creek South vs. Cove Point Hollow
Little Cove Point vs. Seahorse Beach North

Slope Height

The effect of slope height on slope erosion will be evaluated by making comparisons between slopes with similar shoreline characteristics, slope materials, and hydrologic conditions, but different slope height. These comparisons will principally be made entirely within one subsite or between subsites where sufficient control can be maintained. Subsites involved in slope height experiments include:

Randle Cliffs
Governors Run
Parkers Creek South
Scientists' Cliffs North vs. Scientists' Cliffs South
Grovers Creek North vs. Grovers Creek South
Laramie Lane
Driftwood Beach South vs. Seahorse Beach North

Wave Undercutting

Coastal slope erosion is ultimately driven by wave undercutting. Slope erosion and undercutting often follow a cyclic pattern. Waves remove intact material from the slope toe, steepening and destabilizing the slope. Waves also remove the debris produced by slope failures, starting fresh erosion and beginning a new cycle. The magnitude, timing, and water level of the wave erosion is a dominant environmental factor which controls coastal slope erosion. We will investigate the effects of wave undercutting in two ways. In both cases, pairs of sites will be chosen with similar material properties and slope height, but different rates of wave undercutting. In the first case, we will contrast slopes with and without slope toe protection. These comparisons provide the strongest contrast in undercutting rates possible, and also provide a direct investigation of the effectiveness of toe protection works. This set of experiments may identify critical slope toe elevations below which wave undercutting drives the entire slope retreat and above which hydrologic mechanisms dominate. As sea level rises, critical slope toe elevations will rise commensurately. These comparisons will be made at:

Randle Cliffs vs Naval Research Lab North
Naval Research Lab South vs. Holiday Beach
Parkers Creek South vs. Scientists' Cliffs North
Scientists' Cliffs South vs. Governors Run

The second field experiment on wave undercutting will be achieved using similar cliff sections that have a different orientation and, therefore, a different wave energy regime. Along the Calvert County shoreline, such an experiment is possible at two places, Rocky Point and Little Cove Point. At each location, there a significant change in shoreline orientation over a short distance, allowing the cliff height, material properties, and hydrologic domains to be held relatively constant.

5.0 Comparison with Historical Erosion Rates

As discussed in section 1.1, estimates of slope recession over a period of 100 years have been prepared from an analysis of historical maps and modern aerial photographs (Slaughter, 1949). Historical, time-averaged erosion rates provide valuable comparisons for future estimates of slope erosion. However, since coastal slope erosion processes vary over relatively short periods of time, application of historical data to the prediction of erosion rates is restricted to defining the long-term magnitude of the cumulative erosion of a series of short-term erosion episodes.

The purpose of this section is to identify the historical erosion rate at each study site so that an estimate of the long-term rate of slope recession is available from the outset and to provide a measure of comparison for the erosion rates determined in this project.

The historical erosion maps prepared by the Maryland Geological Survey provide erosion rates for shoreline segments and are presented on 1:24,000 scale topographic base maps. An earlier study (Slaughter, 1949) produced shoreline recession rates over a 100 year period. An update of these rates to 1988 is currently underway. Therefore, the time span covered on each quadrangle varies from map to map. The erosion rates are presented as:

S (or s) = slight erosion rate; < 2 feet/year

L (or l) = low erosion rate; 2 - 4 feet/year

M (or m) = moderate erosion rate; 4 - 8 feet/year

H (or h) = high erosion rate; >8 feet/year

A (or a) = indicates accretion

The historical erosion maps do not distinguish between beach erosion or slope erosion. They base their estimate of shoreline erosion on the change in the position of the mean high tide line, or vegetation line where vegetation is present, from the beginning of the period to the end of the period.

Historical erosion rates for the Naval Research Lab site:

Two time periods are used to estimate erosion rates for the shoreline segments along the NRL site. The first is an 87 year period between 1847 and 1934, and the second is a 36 year period between 1934 and 1970.

The resolution of the map does not permit distinction between a beach and a submerged slope toe. However, the bluff top is estimated to have receded approximately 125 feet over the two periods combined (123 years). Hence, the average rate of bluff top recession for this site is 1 foot per year. The only exception to this erosion rate is in the southernmost portion of the site at Holiday Beach where the maximum shoreline recession over the 123 year period is approximately 275 feet or 2.2 feet per year. It should be noted that the slope toe along the Navy Research Lab proper has been protected since the 1930's and has experienced no erosion since then, but the bluff top continues to recede.

Historical erosion rates for the Scientists' Cliffs site:

A single 105 year period, from 1848 to 1953, was used to quantify the shoreline erosion at the Scientists' Cliffs site. During that period the Parkers Creek South subsite shoreline eroded 300 feet for an average rate of approximately 2.8 feet per year. For a short segment of beach near the northern end of the Scientists' Cliffs community where an erosion rate of approximately 1 foot per year is recorded over the period, the Scientists' Cliffs shoreline has accreted or remained nearly stable, although bluff top retreat continues. The shoreline along the Governors Run subsite shows no net loss or gain over the 105 year period, while the upper portions of the slope have receded.

The shoreline along the Scientists' Cliffs community has been partially protected by gabion groins which have helped to establish a beach. Anecdotal information provided by Scientists' Cliffs residents indicates an average bluff top recession of approximately 0.5 feet per year.

Historical erosion rates for the Calvert Cliffs State Park site:

A single 94 year period, from 1849 to 1943, was used to quantify the shoreline erosion at the Calvert Cliffs State Park site. Once again, the maps do not distinguish between beach or slope erosion, making the estimates near the Cove Point or southern end of the site difficult to interpret. Cove Point is a marshy, low lying point of sand and silt which has slowly been migrating south over the past 150 years. It is postulated that a significant beach was present in the late 1800's and early 1900's on the northern portion of the current Columbia Liquid Natural Gas property immediately south of the Calvert Cliffs State Park. This assumption is supported by the offshore remnants of a salt marsh in this vicinity. The current salt marsh is well south of the state park and protected by a barrier beach.

The historical erosion map indicates that approximately 400 feet (4.5 feet/year) of shoreline have been eroded from the central portions of this site in the 94 year period. A lower rate of approximately 1 foot per year occurs just south of Rocky Point (at the northern end of the site) and a higher rate of 6.4 feet per year is indicated for the extreme southern portion of the site near the submerged salt marsh.

Two structures present on the state park property, one at the northern end just north of Grover Creek and one at the southern end south of Grays Creek, help to establish a rate of bluff top recession between 1943 and 1987 of approximately 4 feet per year (180 feet in 44 years).

Historical erosion rates for the Chesapeake Ranch Estates site:

A single 96 year period, from 1848 to 1944, was used to quantify the shoreline erosion at the Chesapeake Ranch Estates site. The rate of shoreline erosion during this period ranges from near zero at the mouth of Parker Moore Creek near the central portion of this site to approximately 2 feet per year both to the north and to the south of Parker Moore Creek.

At Little Cove Point the shoreline has remained nearly stable, but the shoreline several hundred feet to the north and south has receded an average of slightly over 2 feet per year. The maximum shoreline erosion over this 96 year period was approximately 2.4 feet per year and occurred at the northern end of the CRE site between Little Cove Point and Cove Point Hollow.

It should be noted that the Chesapeake Ranch Estate property has been substantially developed since 1944. Field observations indicate that the rate of slope erosion is accelerating north of Seahorse Beach and north of Driftwood Beach.

Summary and discussion of the historical erosion rates along the Calvert Cliffs

Table 4 summarizes the historical erosion rates at each site. Generally, the historical rate of recession of the mean high tide or vegetation line increases southward along the Calvert Cliffs. Notable exceptions occur where shoreline protection has been constructed, where local induration has occurred, and at the southernmost study site, the Chesapeake Ranch Estates, where the slopes are generally taller than those at the other study sites. The trend of higher slope toe erosion rates toward the south correlates well with the decreasing age (and decreasing consolidation) of the stratigraphic materials southward. Exceptions occur where factors other than the erodibility of the material in the toe zone exert an influence. For instance, bulkheads and groins reduce or eliminate the wave impact on the slope toe and reduce recession rates. Local induration provides increased material resistance to erosion and locally diminishes recession rates. Tall slopes contain greater volumes of material than shorter slopes; material which must be removed before shoreline recession can take place. For tall slopes, the rate of removal must be substantially greater than that for shorter slopes for equal amounts of shoreline recession to be observed.

Local and short-term variations in shoreline recession (ie. variations within individual study sites) tend to be obscured by long-term, time-averaged recession rates. However, such variations may be extremely significant because of their implications for property owners, land-planners, officials responsible for public safety, and bay sediment supply and transport evaluations. Both the Naval Research Laboratory and Scientists' Cliffs study sites offer opportunities to evaluate the effect of protective structures on slope stability. Where shore protection is in-place at both sites, the bluff tops continue to recede. However, recession is evident for the entirety of the unprotected slopes at both locations. Scientists' Cliffs offers a particularly good site for evaluating the impact of gradual increases in sea-level because the position of the slope toe relative to the water level gradually changes across the length of the site. Here, the conditions range from no protection to complete protection. The two southernmost sites (ie. Calvert Cliffs State Park and the Chesapeake Ranch Estates) have varying shoreline orientations and no toe protection. These conditions allow the effect of wave climate on short-term slope stability to be evaluated. Also, the differences in slope height between the two southern sites allows a comparison to be made regarding the effect of slope height on short-tern failure modes and patterns of sequential erosion processes.

Table 4. - Summary of Historical Erosion Rates

Site - subsite	Historical erosion rate (ft/yr) averaged over at least 96 years.	Comments
NRL - Randle Cliffs	1	
NRL - Naval Research Lab North	1	60 years of toe protection, bluff top continues to recede
NRL - Naval Research Lab South	1	60 years of toe protection, bluff top continues to recede
NRL - Holiday Beach	2.2	Highest recession where slope heights are lowest.
SC - Parkers Creek	2.8	
SC - Scientists' Cliffs North	1	
SC - Scientists' Cliffs South	Stable shoreline	60 years of toe protection, bluff top continues to recede
SC - Governor Run	Stable	Field observations indicate active slope erosion, historical map accuracy is questionable.
CCSP - Rocky Point	1.0	Local induration present.
CCSP - Grover Creek North	4.5	
CCSP - Grover Creek South	4.5	
CCSP - Grays Creek South	4.5	A higher historical rate of 6.4 ft/yr occurs in the vicinity of salt marsh
CRE - Little Cove Point	Stable	Local induration present. Just north and south of LCP the average rate is approx. 2 ft/yr.
CRE - Laramie Lane	2	Relatively tall slopes.
CRE - Driftwood Beach South	2	Relatively tall slopes.
CRE - Seahorse Beach North	2	Relatively tall slopes.

6.0 Extrapolation of Observations to Other Portions of the Chesapeake Bay Shoreline

There is very little variation in the climate and physiography over the Maryland portion of the Chesapeake Bay. Therefore, the variation in slope materials and their orientation relative to bay wave conditions are the primary factors that determine where shoreline erosion will occur. In addition to the eroding coastal slopes of the western shore of the Chesapeake Bay, tall, eroding slopes are present in the northeastern portions of the bay and along many of the bay tributaries. The mechanics-based methodology for evaluating coastal slope instability developed during CCSEP may be extrapolated to the eroding coastal slopes baywide. Where similar materials occur, the particular results we find for Calvert County may be directly applied. When extending this model to other locations, variations in shoreline orientation (wave climate), slope height, and material properties must be accounted for. The wave climate depends on the geographic location of the slope under consideration and can be evaluated by assessing the bathymetric configuration, principal wind direction, and slope toe elevation at the site.

A conservative extrapolation of the Calvert Cliffs results to other sites would require that the range of materials comprising the slope in question be similar to those materials comprising the Calvert Cliffs. The geology of the slopes bordering the bay must be considered in any such extrapolation.

The Calvert Cliffs are principally composed of the Chesapeake Group and are upper Tertiary, Miocene Epoch coastal plain sediments ranging in age from the lower Calvert Formation at 21.5 million years through the Choptank Formation to the upper Saint Marys Formation with an age of 10.4 million years years (Kidwell, 1984).

The Calvert Formation represents deposition in an inner to possibly middle shelf marine environment, the Choptank is mainly marine inner shelf, and the Saint Marys Formation was deposited in a very shallow shelf to marginal marine environment (Olsson, et. al., 1988). The sediments are relatively undeformed and unlithified marine, terrigenous silts, sands, and clays (Kidwell, 1982).

The Calvert Cliffs (Chesapeake Group) are composed of interbedded fossiliferous sands, gravelly sands, silts, and clays. Ironstone forms in laterally discontinuous patches and is the most indurated material present in the slope materials. There are typically large contrasts of material strength and hydraulic conductivity between stratigraphic units in the Calvert Cliffs. Because these units dip gently along the shoreline, there are also contrasts in material strength along the cliffs.

Figure 6.1 shows the surface distribution of major Cretaceous (146 million to 65 million years before present) and Tertiary (65 million to 1.64 million years before present) coastal plain sediments along the Chesapeake Bay (Wheeler, 1990). The materials baywide are all part of the same coastal plain depositional suite and are principally interbedded sands, silts, and clays (Olsson, et. al., 1988). In surface exposure, they become older to the north. Thin veneers of Pliocene and Pleistocene materials may be present at the surface around much of the bay.

Referencing Figure 6.1 and moving from south to north (youngest to oldest) through the major formations exposed at the surface:

Chesapeake Group - discussed above

*Aquia Formation - The Aquia is lower Tertiary in age (approximately 60 million years old) and is comprised of a shelly glauconitic sand deposited in a very shallow shelf environment. It is overlain by the Marlboro Clay a marginal marine deposit.

*Magothy Formation - The Magothy is composed of a series of cross-bedded sands with thin beds of clays, silts, and scattered lignite. It was formed as a beach zone complex with related fluvial and estuarine facies. It is upper Cretaceous in age (approximately 85 million years old).

*Potomac Group - The Potomac Group is the basal sequence of sedimentation on the coastal plain outcrop. It is composed of white, gray, and red interbedded variegated silts, clays, and quartzose sands. It fluvial-deltaic depositional environment of a major river system. The Potomac Group is lower Cretaceous in age and spans at least 67 million years from 132 million years before present to 65 million years before present.

An important application of the methodology developed by CCSEP is the prediction of slope erosion mechanisms and rates at other locations along the Chesapeake Bay. Toward this end, Figure 6.2 presents a conceptual model which outlines the data required and the logical sequence that could be used to estimate slope erosion at sites beyond Calvert County. An important feature of this model is the relatively small amount of data needed to identify specific mechanisms of slope erosion and the rates at which they operate.

Specific site assessments for any particular coastal slope would require the location of the slope, the elevations of the slope toe and bluff top, and the average slope angle from the slope toe to the bluff top (or the horizontal distance between the toe and the bluff top). The geometric data can be obtained from a detailed topographic map or from a simple survey of the slope toe and bluff top. With this information, the type of slope (Type I, II, III, or IV) and, therefore, the types and relative rates of erosion mechanisms, could be determined. With a map of the exposed coastal plain sediments around the bay and a description of their general properties, the slope location may be used t estimate the geotechnical and hydrologic properties of the slope materials. A map of wave climate for design storms on the bay would provide an estimate of undercutting rates at the site. With this information, the general combined CCSEP model could be applied to determine the dominant mechanisms of the slope erosion at the site, and the long term recession rates. This information can then be used to evaluate slope protection methods, estimate non-point source sediment supply to the bay, and determine policy on slope protection, setback distances, and public safety. Prediction of the probability and timing of individual large slope failures in the short term will depend on the particular geometry of the slope at any given time, and short-term predictions would require a detailed site investigation of the hydrologic properties and slope geometry. This detailed information is not necessary, however, for predicting the long-term recession rates, which are driven by the cumulative effect of many individual failures and are less dependent on the detailed geometry of the slope at any time.

7.0 References

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Table 1 - Physical Characteristics of CCSEP sites and subsites

Site Name Subsite Name (listed from north to south)	Site Name Abbrv.	Shoreline Orientation	Slope Height/Shape (meters/degrees)	Toe Protect.	Long- shore Bars	Slope Type
Naval Research Lab	NRL					
Randle Cliffs	RC	E	18-27 / <=90	None	Yes	IV
Naval Research Lab North	NRLN	ENE	18-34 / 30-90	Seawall	No	I
Naval Research Lab South	NRLS	ENE	30-32 / 30-90	Seawall	No	I
Holiday Beach	HB	ENE	20-34 / 70	None	Yes	IIIA
Scientists Cliffs	SC					
Parker Creek South	PCS	ENE	15-30 / 50-90	None	Yes	IV and IIIA
Scientists Cliffs North	SCN	ENE	15-29 / 45-60	Beach	Yes	IIIA
Scientists Cliffs South	SCS	ENE	20-29 / 35-60	Beach	Yes	I
Governor Run	GR	ENE	18-36 / 50-80	None	Yes	IIIA
Calvert Cliffs State Park	CCSP					
Rocky Point	RP	NE,ENE,E	15-35 / 65-85	None	No	IIIB
Grover Creek North	GVCN	NE	12-18 / 50-60	None	No	IIIA
Grover Creek South	GVCS	NE	15-30 / 50-60	None	No	IIIA and IIIC
Grays Creek South	GYCS	ENE	15-25 /50- 60	None	No	IV
Chesapeake Ranch Estates	CRE					
Cove Point Hollow	CPH	ENE	10-25/30-90	None	Yes	IIIA and IIIC
Little Cove Point	LCP	NE,E,ESE	16-22 / 30-60	None	Vague	II
Laramie Lane	LL	ESE	15-35 / 40-90	None	Yes	IIIC
Driftwood Beach South	DBS	SE	16-22 / 60-80	None	Yes	IIIC
Seahorse Beach North	SBN	SE	12-30 / 65-85	None	Vague	IIIC

Table 2 - CCSEP Experiments

	NAVAL RESEARCH LAB				SCIENTISTS CLIFFS				C. C. STATE PARK				CHES. RANCH ESTATES				
Experiment	RC	NRLN	NRLS	HB	PCS	SCN	SCS	GR	RP	GVCN	GVCS	GYCS	CPH	LCP	LL	DBS	SBN
MATERIAL PROPERTIES																	
	X			X													
					X			X									
									X			X					
				X	X												
				X									X				
					X								X				
														X		X	
														X			X
SLOPE HEIGHT																	
	XX																
					XX												
						X	X										
								XX									
										X	X						
															XX		
																X	X
SHORELINE PROTECTION																	
	X	X															
			X	X													
					X	X											
							X	X									
SHORELINE ORIENTATION																	
									XX								
														XX			

Appendix A

Table A1: Sedimentological parameters - split spoon samples collected January 23-31, 1991 - Navy Research Lab

Well number	Depth to top of sample (ft)	(m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
NRL1	3.0	0.9	17.18	44.75	21.19	34.06	SaSiCl	9.53
NRL1	8.0	2.4	10.72	56.15	24.85	18.99	SiSa	8.41
NRL1	13.0	4.0	17.10	57.84	21.31	20.85	SaSiCl	9.12
NRL1	18.0	5.5	22.92	70.20	14.45	15.35	ClSa	0.79
NRL1	23.0	7.0	34.09	57.26	22.77	19.97	SiSa	8.00
NRL6	25.0	7.6	31.00	56.12	24.80	19.08	SiSa	6.75
NRL1	28.0	8.5	35.70	50.87	26.39	22.74	SaSiCl	9.12
NRL1	33.0	10.1	46.34	21.34	50.79	27.88	SaSiCl	9.30
NRL1	38.0	11.6	26.64	74.91	14.15	10.94	SiSa	11.93
NRL1	43.0	13.1	37.54	40.68	29.01	30.31	SaSiCl	15.56
NRL1	48.0	14.6	26.98	95.57	3.21	1.21	Sa	24.66
NRL1	53.0	16.2	26.02	87.86	8.63	3.51	Sa	10.31
NRL1	58.0	17.7	33.35	77.37	11.87	10.76	Sa	4.74
NRL1	63.0	19.2	37.32	59.85	22.13	18.02	SiSa	9.63
NRL1	68.0	20.7	36.21	62.58	20.28	17.14	SiSa	13.23
NRL1	73.0	22.3	32.28	77.42	11.71	10.87	Sa	5.16
NRL1	78.0	23.8	31.27	69.64	17.84	12.52	SiSa	12.69
NRL1	83.0	25.3	32.73	40.32	35.63	24.06	SaSiCl	13.12
NRL1	88.0	26.8	37.57	19.65	48.07	32.28	ClSi	13.54

Table A2: Sedimentological parameters - split spoon samples collected January 14-17, 1991 - Scientists' Cliffs

Well number	Depth to top of sample (ft)	(m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
SC1	5.0	1.5	14.11	83.98	11.22	4.80	Sa	1.92
SC1	15.0	4.6	27.95	51.45	26.92	21.62	SaSiCl	----
SC1	20.0	6.1	13.90	88.02	4.77	7.21	Sa	47.81
SC1	25.0	7.6	13.90	91.00	4.65	4.35	Sa	35.49
SC1	30.0	9.1	23.43	83.56	7.64	8.80	Sa	3.73
SC1	35.0	10.7	25.06	77.46	12.26	10.28	Sa	12.18
SC1	40.0	12.2	29.22	64.04	17.82	18.14	ClSa	7.53
SC1	45.0	13.7	29.68	43.99	32.36	23.65	SaSiCl	9.83
SC1	50.0	15.2	28.44	25.66	40.08	34.26	SaSiCl	15.83
SC1	55.0	16.8	14.76	82.70	8.47	8.83	Sa	32.49
SC1	60.0	18.3	15.50	92.32	3.63	4.05	Sa	8.49
SC1	65.0	19.8	19.31	93.74	4.89	1.37	Sa	13.61
SC1	70.0	21.3	21.89	93.66	4.53	1.81	Sa	9.86
SC1	75.0	22.9	26.74	66.30	14.96	18.74	ClSa	13.96
SC1	80.0	24.4	24.13	75.71	10.92	13.37	Sa	7.94
SC1	85.0	25.9	25.04	79.70	12.34	7.96	Sa	8.59

Table A3: Sedimentological parameters - split spoon samples collected December 17-20, 1990 - Calvert Cliffs State Park

Well number	Depth to top of sample (ft)	Depth to top of sample (m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
CCSP1	5.0	1.5	3.01	86.19	7.20	6.61	Sa	2.83
CCSP1	10.0	3.0	14.69	16.08	41.73	42.19	SiCl	6.95
CCSP1	15.0	4.6	16.09	41.52	33.52	24.97	SaSiCl	2.24
CCSP1	20.0	6.1	11.47	70.66	12.85	16.48	ClSa	2.06
CCSP1	25.0	7.6	18.87	81.15	9.61	9.24	Sa	2.36
CCSP1	30.0	9.1	18.48	78.76	11.16	10.08	Sa	3.02
CCSP1	30.8	9.4	20.16	79.99	11.06	8.94	Sa	3.53
CCSP1	35.0	10.7	22.18	79.58	12.18	8.24	Sa	2.41
CCSP1	40.0	12.2	22.58	19.59	35.28	45.13	SiCl	6.20
CCSP1	45.0	13.7	19.08	28.08	30.63	41.29	SaSiCl	9.49
CCSP1	50.0	15.2	18.78	25.91	29.05	45.04	SaSiCl	11.40
CCSP1	55.0	16.8	23.19	21.18	39.00	39.82	SaSiCl	13.39
CCSP1	60.0	18.3	21.82	38.65	39.14	22.20	SaSiCl	7.80
CCSP1	65.0	19.8	23.00	3.15	70.26	26.59	ClSi	7.77
CCSP1	70.0	21.3	26.42	10.97	44.70	44.33	ClSi	9.26
CCSP1	75.0	22.9	19.60	87.64	5.79	6.57	Sa	11.80

Table A4: Sedimentological parameters - split spoon samples collected December 6-10, 1990 - Chesapeake Ranch Estates

Well number	Depth to top of sample (ft)	(m)	Water (%)	Sand (%)	Silt (%)	Clay (%)	Shepard's class	Weight loss (%)
CRE1	4.5	1.4	10.58	48.62	38.69	12.70	SiSa	5.69
CRE1	9.5	2.9	5.46	90.62	3.95	5.43	Sa	1.68
CRE1	14.5	4.4	4.97	93.91	3.21	2.87	Sa	1.64
CRE1	19.5	5.9	5.95	94.36	2.49	3.16	Sa	1.64
CRE1	24.5	7.5	5.58	94.13	2.47	3.40	Sa	1.69
CRE1	29.5	9.0	10.89	92.80	1.70	5.50	Sa	3.13
CRE1	34.5	10.5	11.05	88.75	5.46	5.80	Sa	3.06
CRE1	39.5	12.0	12.07	92.78	3.64	3.59	Sa	2.52
CRE1	44.5	13.6	13.23	80.72	7.99	11.29	Sa	5.10
CRE1	49.5	15.1	14.58	65.09	17.84	17.07	SiSa	3.48
CRE1	50.0	15.2	26.57	10.27	30.10	59.62	SiCl	5.74
CRE1	50.5	15.4	19.28	47.42	25.23	27.35	SaSiCl	7.93
CRE1	54.5	16.6	13.31	69.99	14.89	15.12	ClSa	6.40
CRE1	59.5	18.1	17.83	75.63	10.94	13.43	Sa	7.09
CRE1	64.5	19.7	20.60	69.95	17.82	12.23	SiSa	4.18
CRE1	69.5	21.2	19.68	53.27	33.06	13.67	SiSa	23.07
CRE1	74.5	22.7	20.31	77.37	16.47	6.16	Sa	34.62
CRE1	79.5	24.2	20.65	32.89	49.67	17.43	SaSi	9.94
CRE1	84.5	25.8	22.73	5.00	38.02	56.98	SiCl	15.08

FIGURE 2.1 STUDY SITE LOCATIONS: CALVERT CLIFFS SLOPE EROSION PROJECT

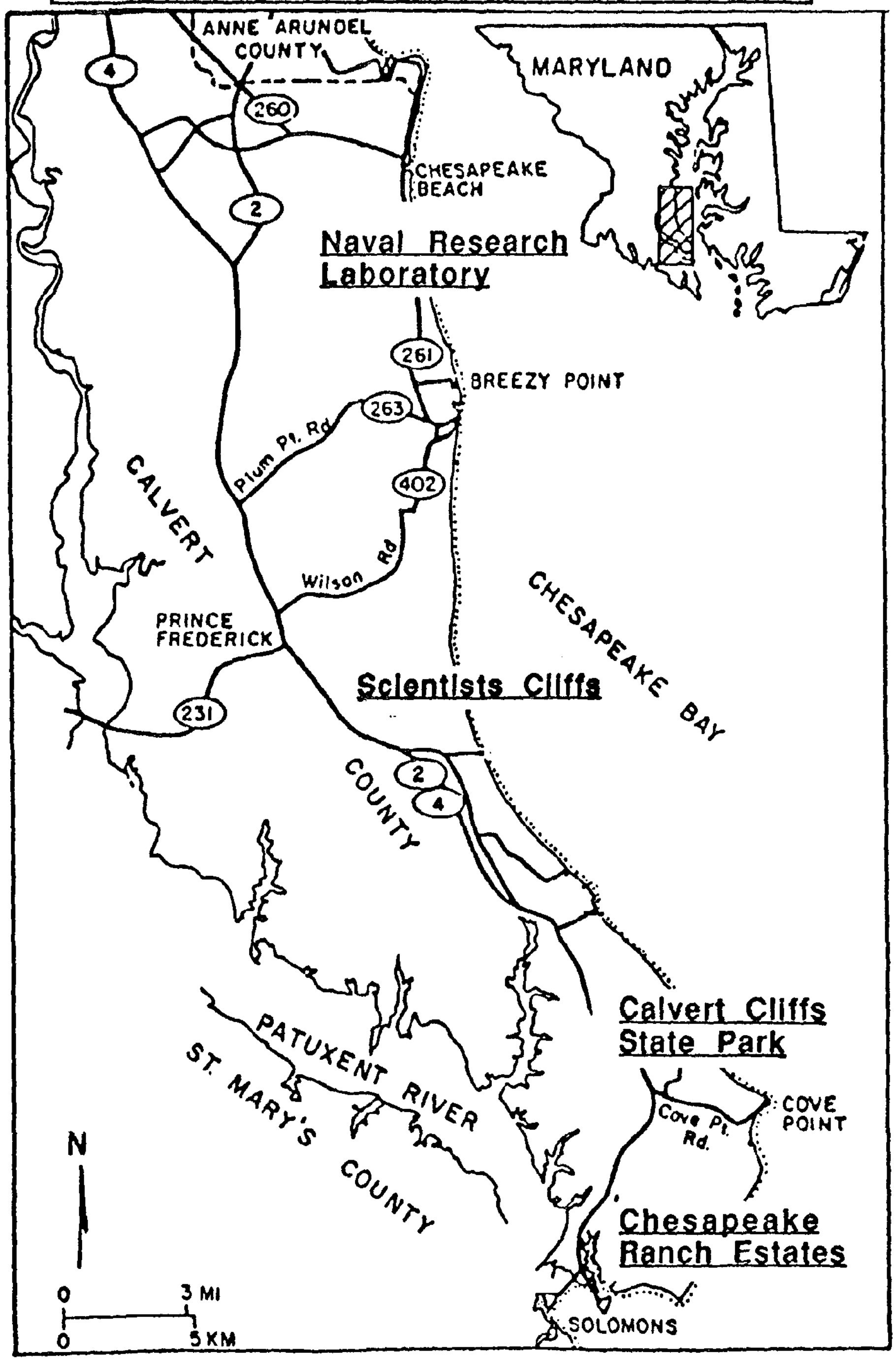


Figure 3.1 Study Site NRL: Naval Research Laboratory

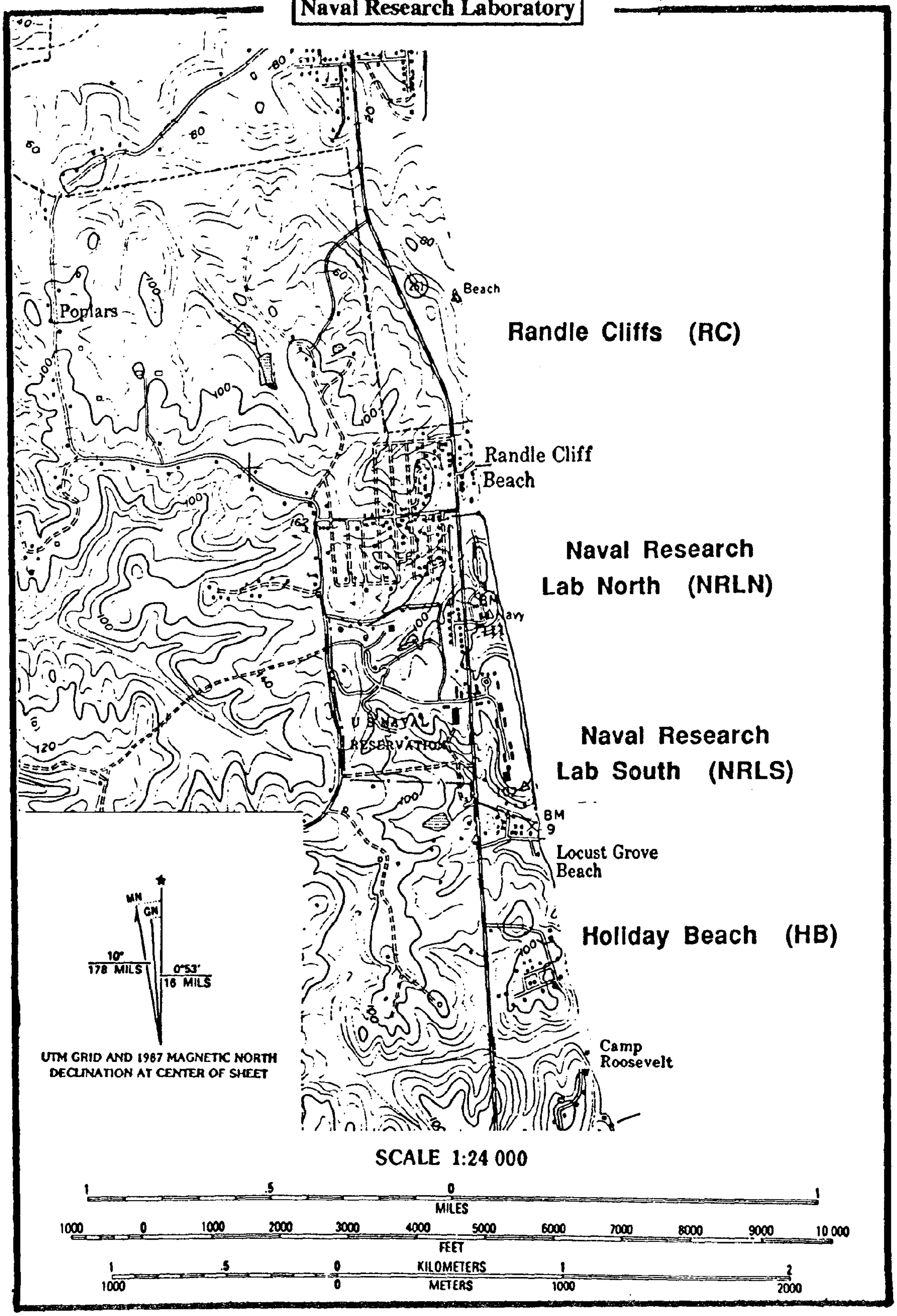


Figure 3.2a Randle Cliffs North Slope Profile

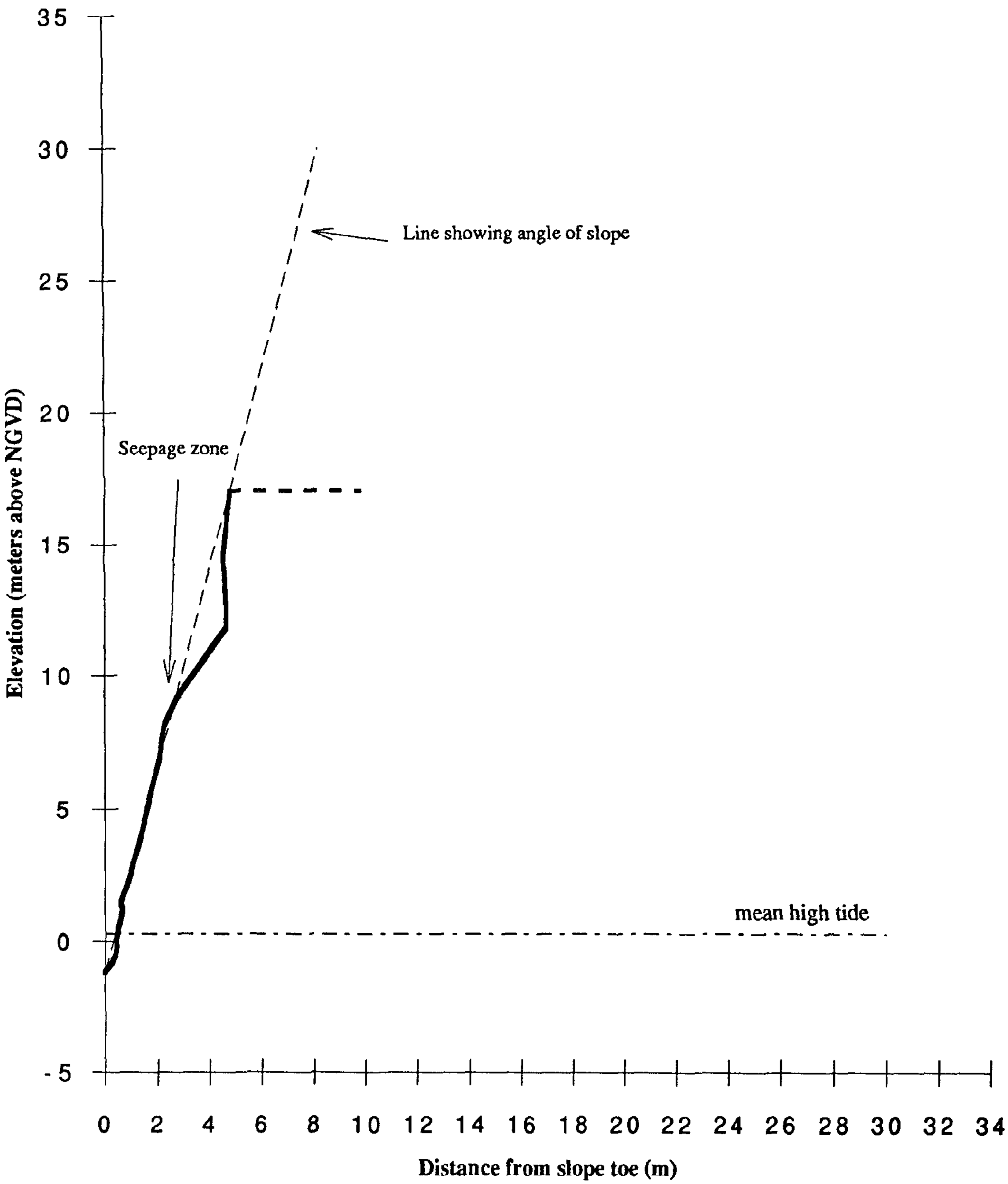


Figure 3.2b Randle Cliffs South Slope Profile

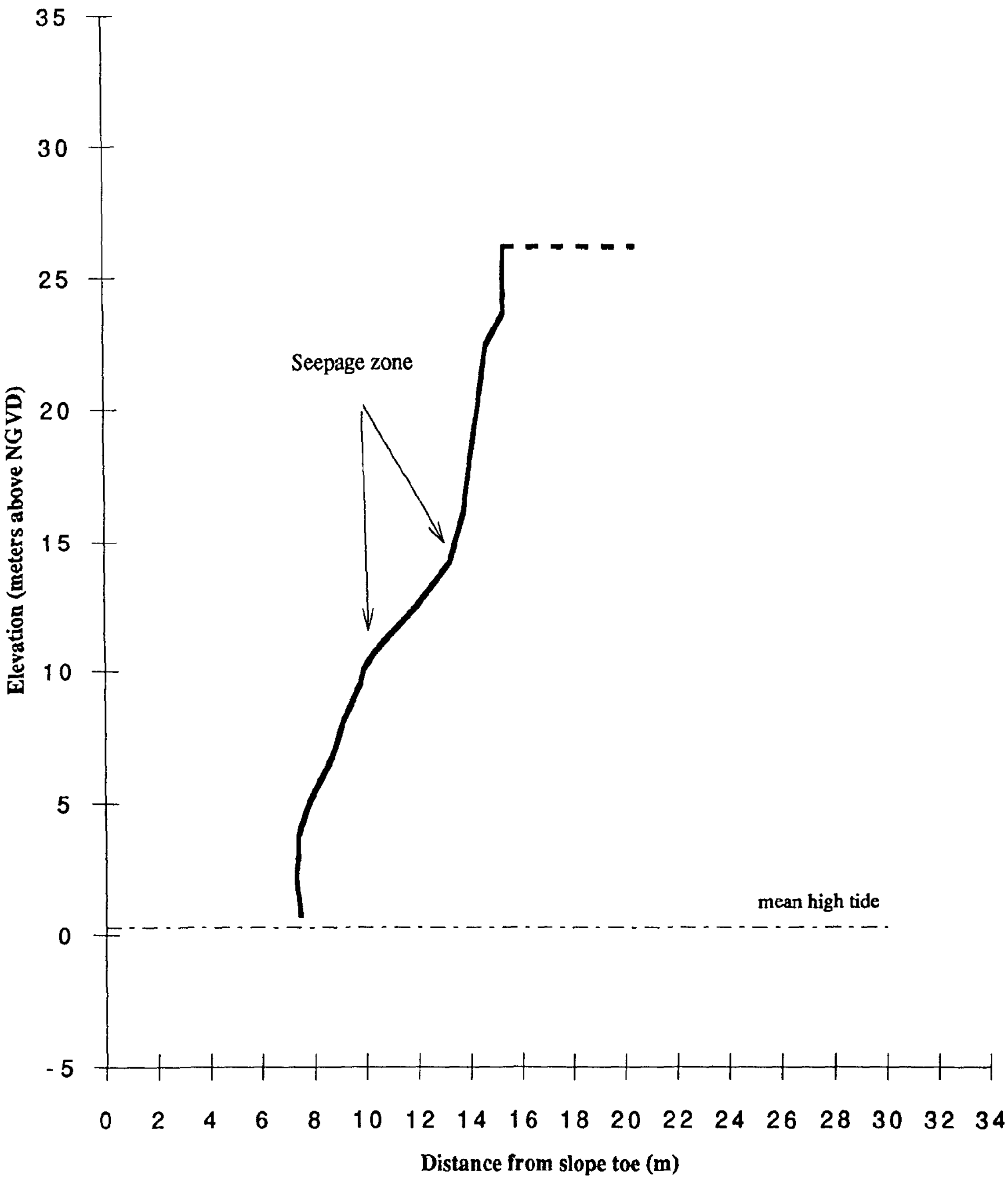


Figure 3.2c Naval Research Laboratory Slope Profile

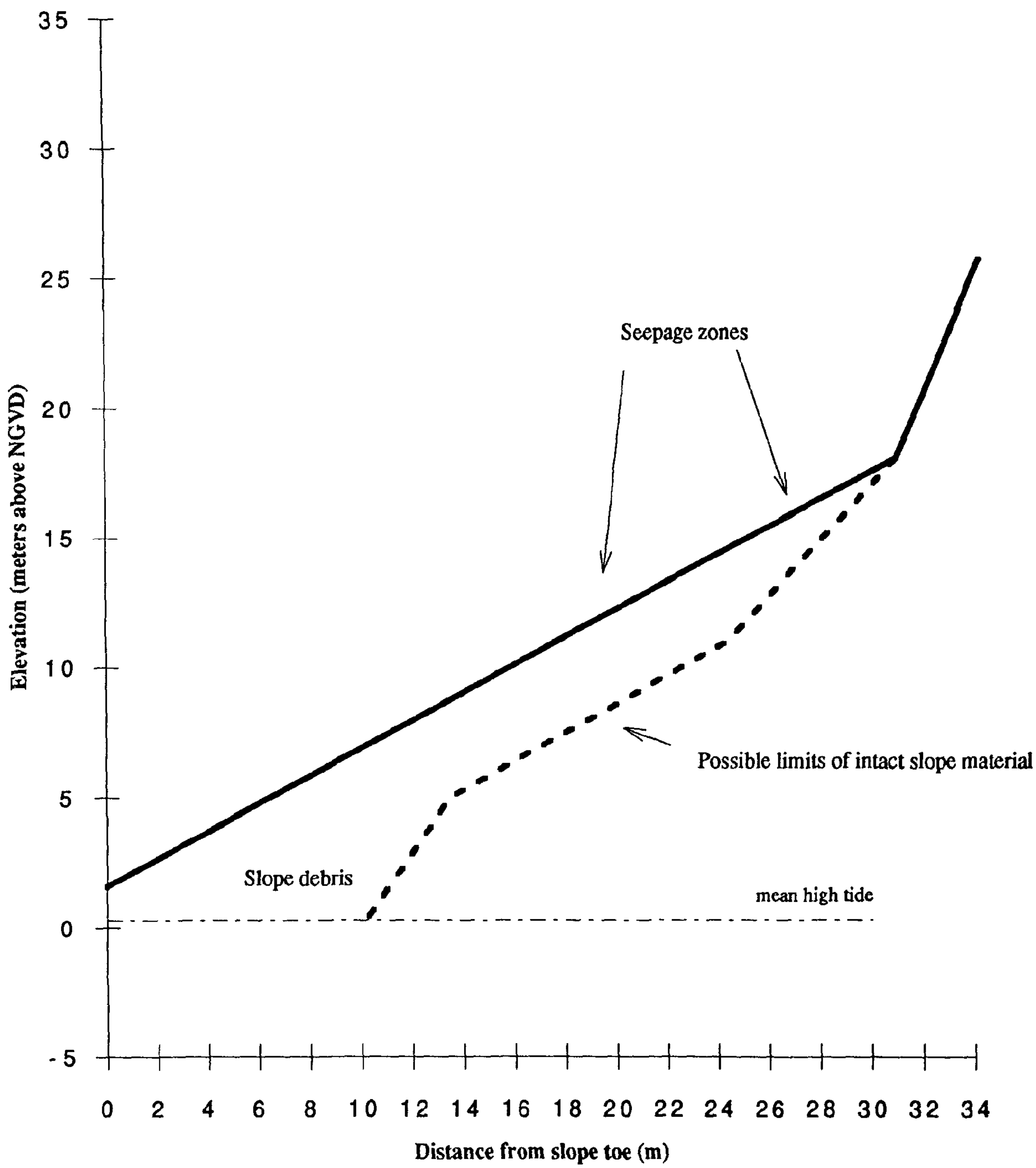


Figure 3.3: Naval Research Lab Geotechnical Profile

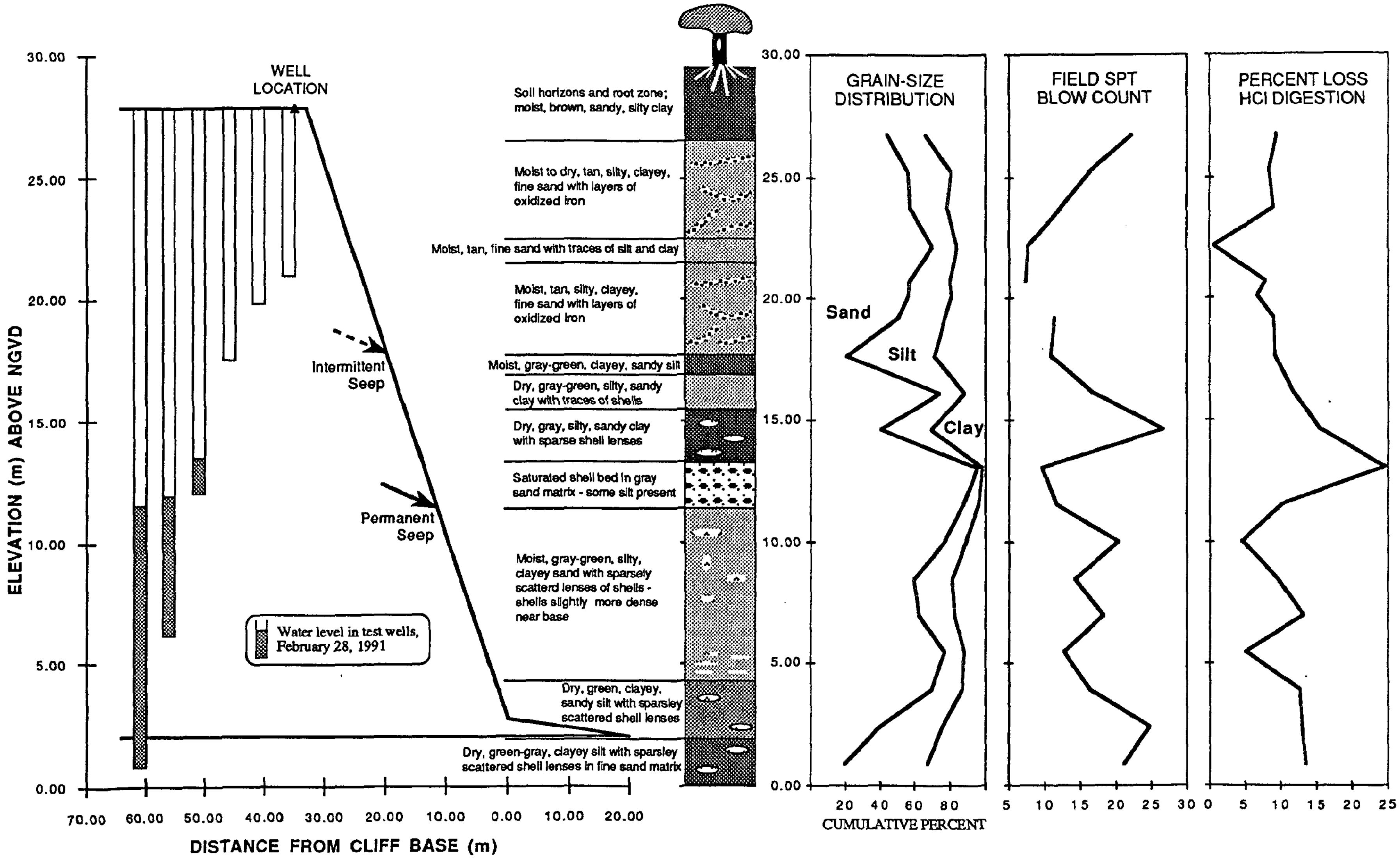


Figure 3.4 Study Site SC: Scientists' Cliffs

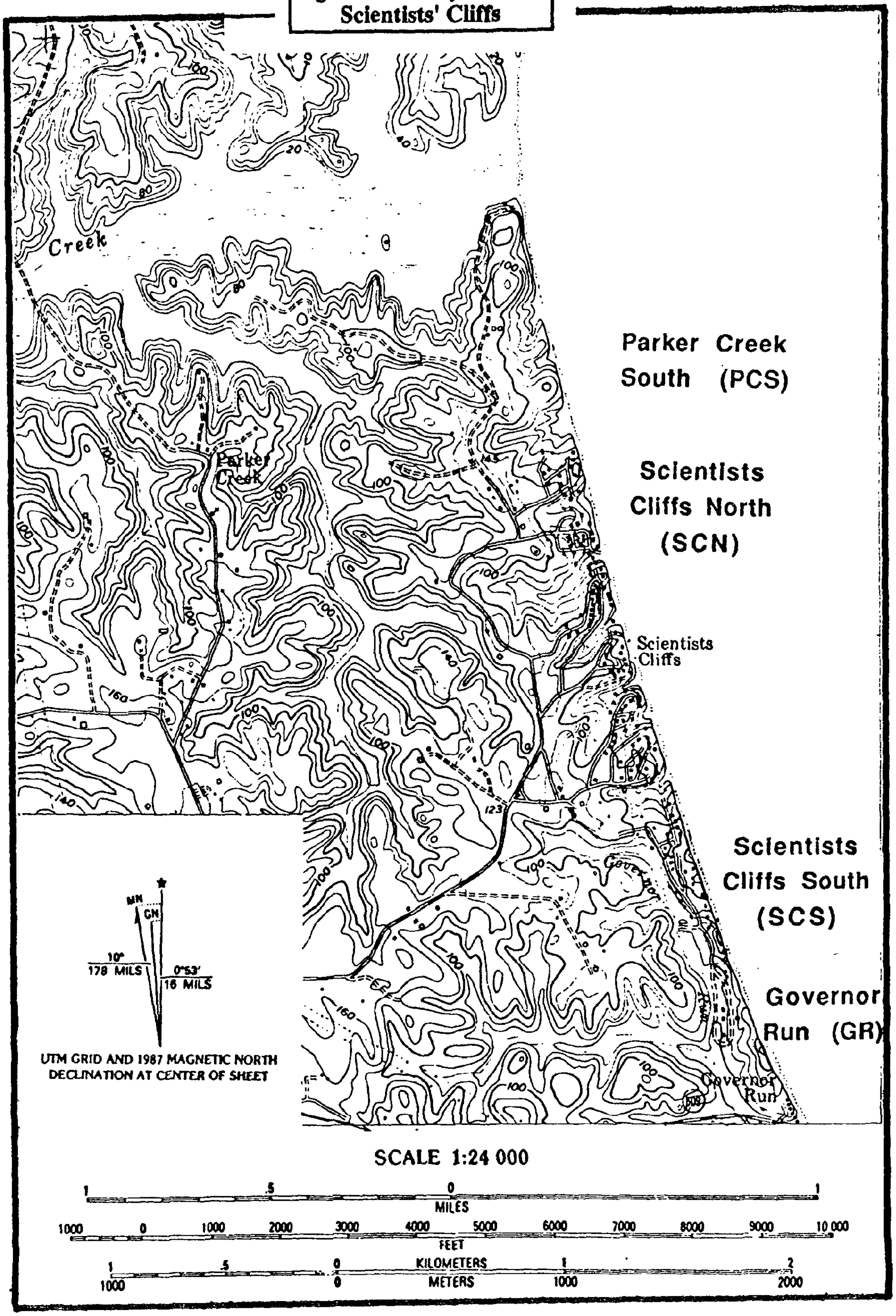


Figure 3.5a Parkers Creek Slope Profile

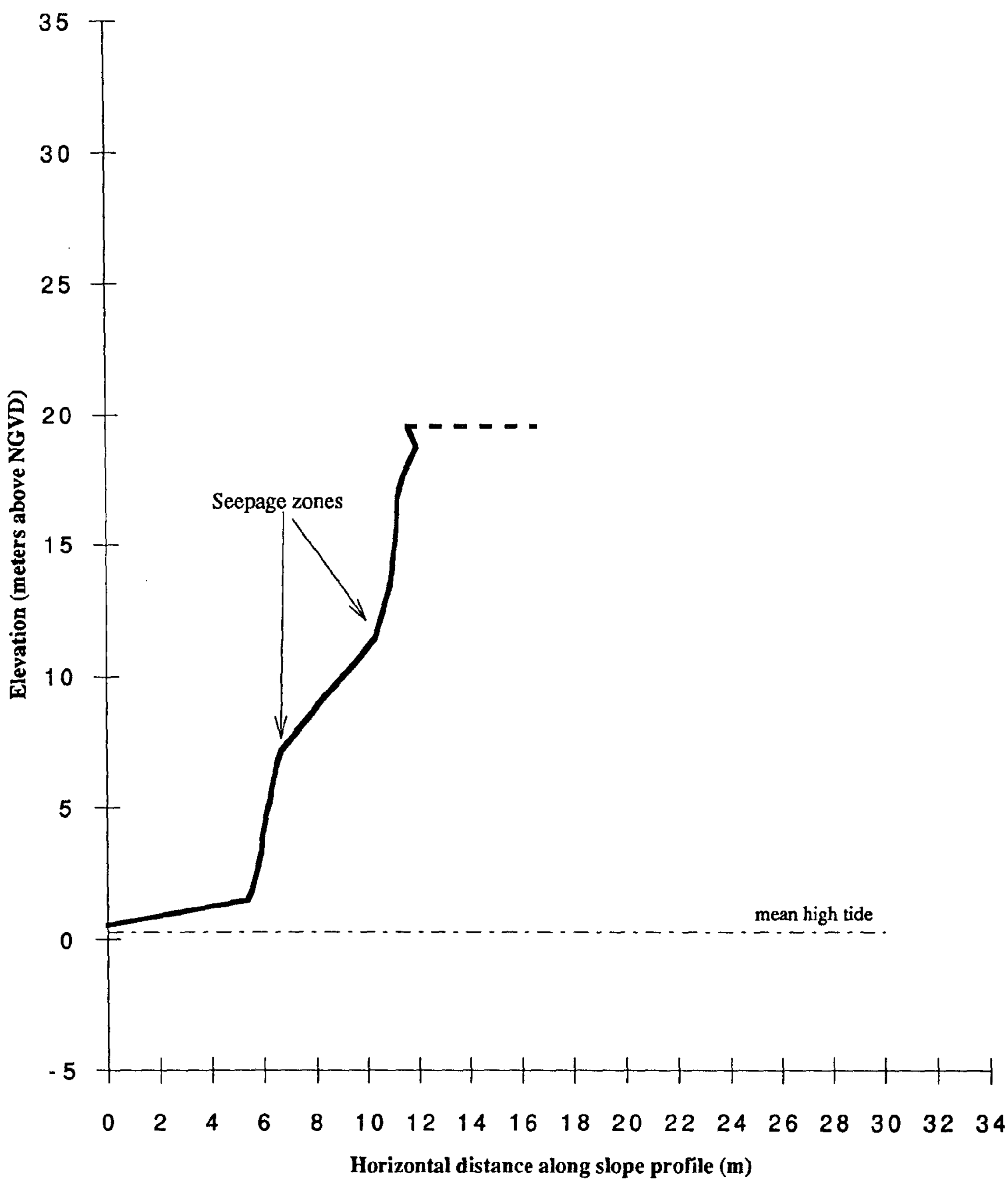


Figure 3.5b Scientists' Cliffs North Slope Profile

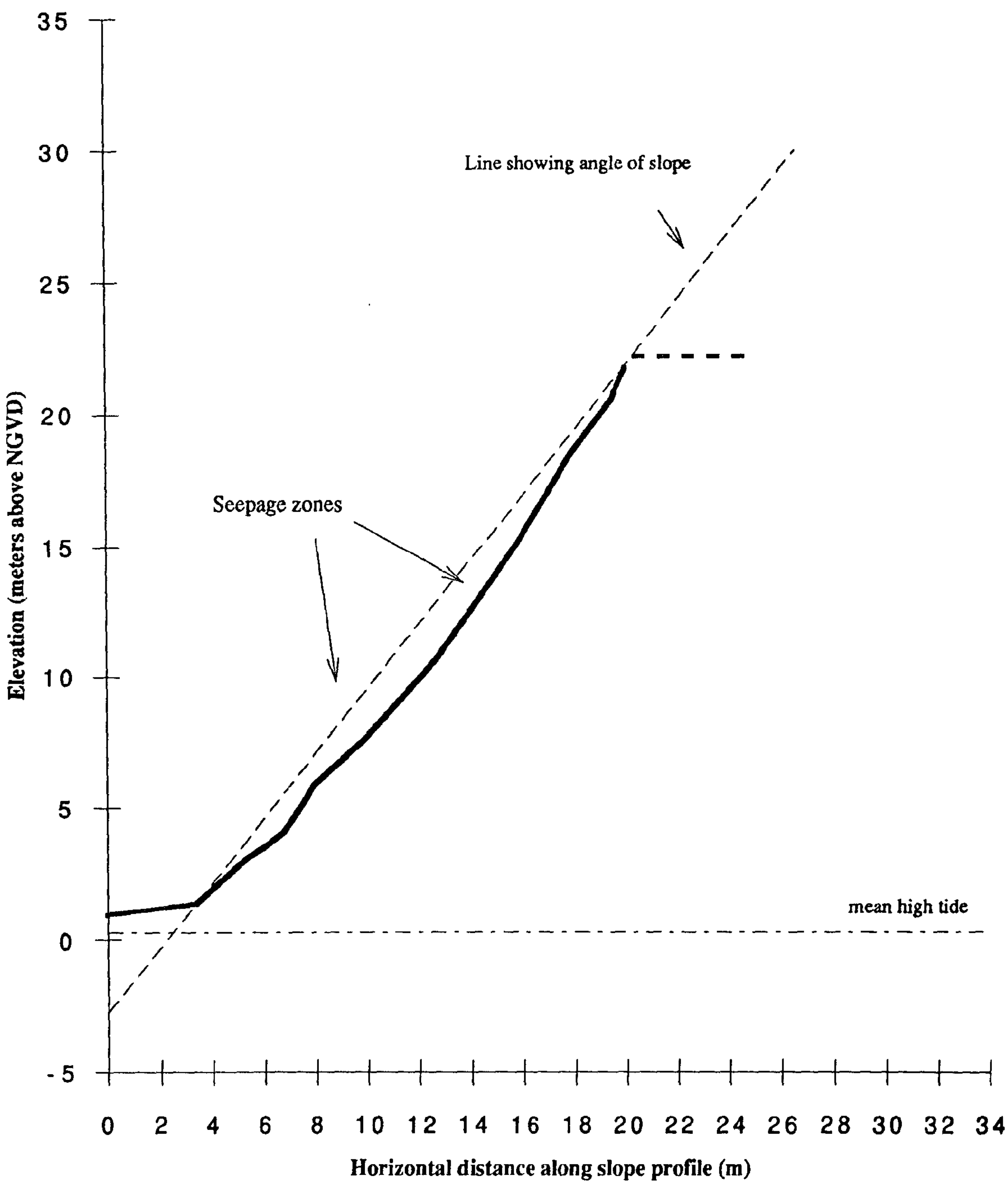


Figure 3.5c Scientists' Cliffs South Slope Profile

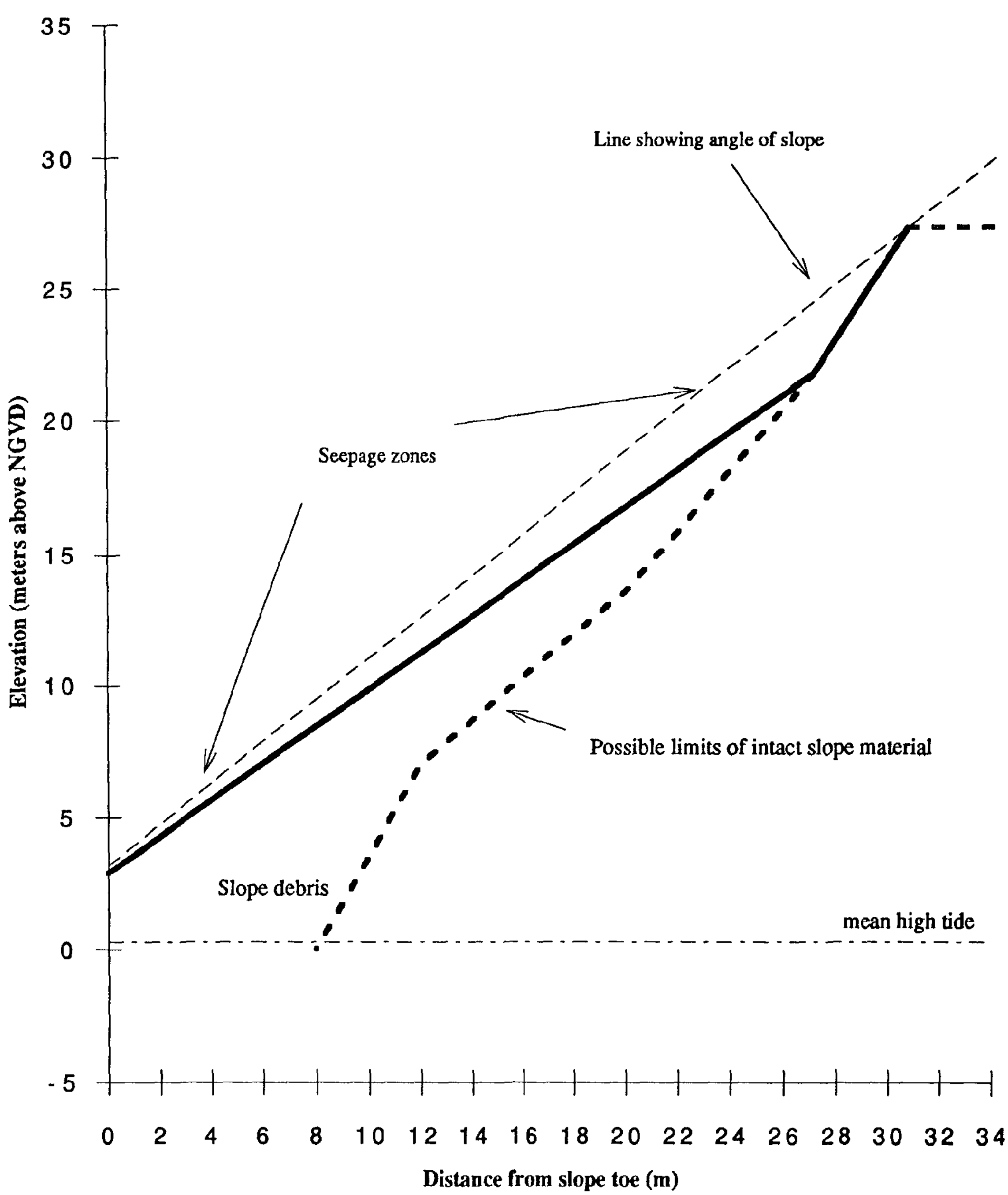


Figure 3.5d Governor's Run Slope Profile

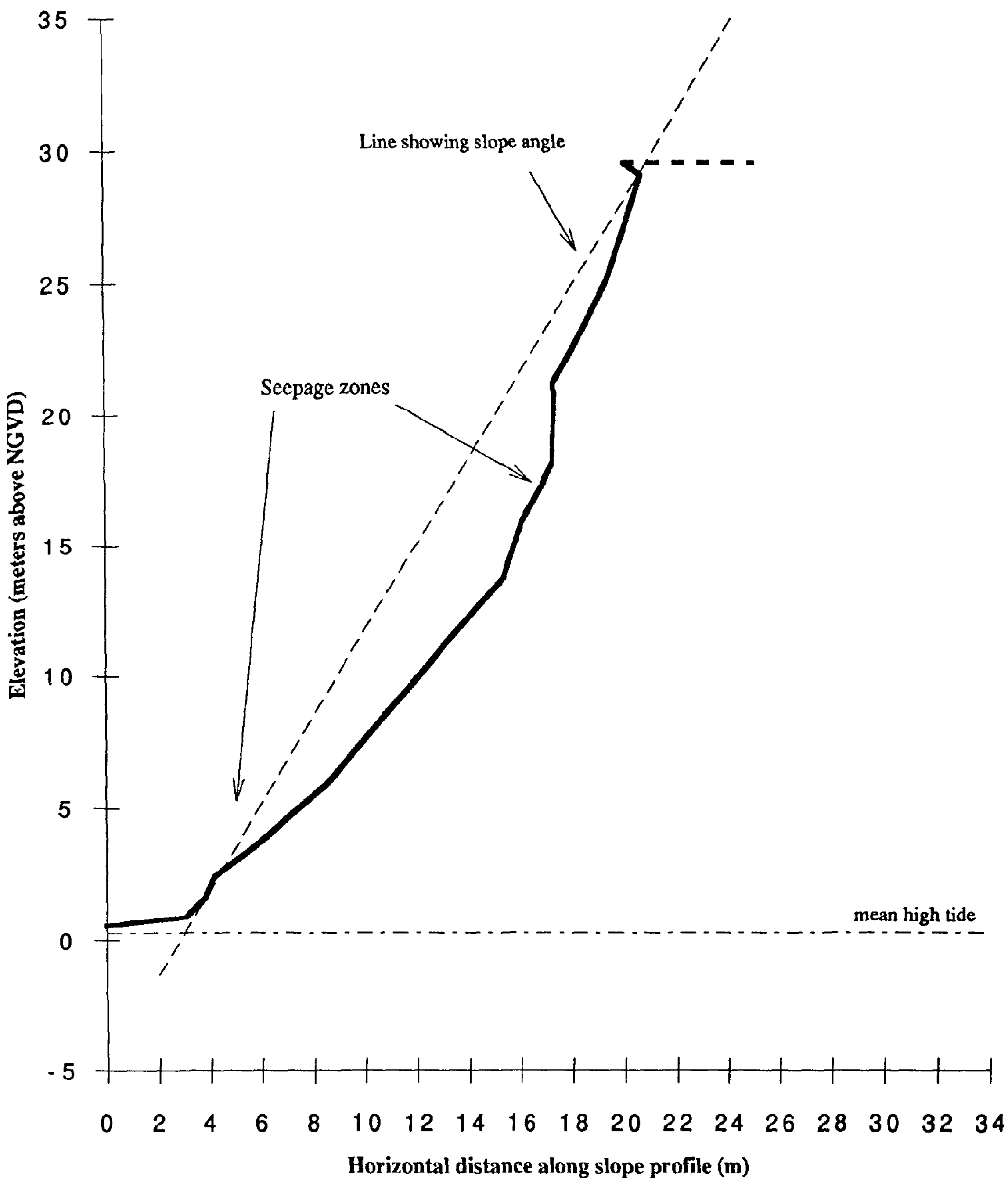


Figure 3.6 Scientists' Cliffs Geotechnical Profile

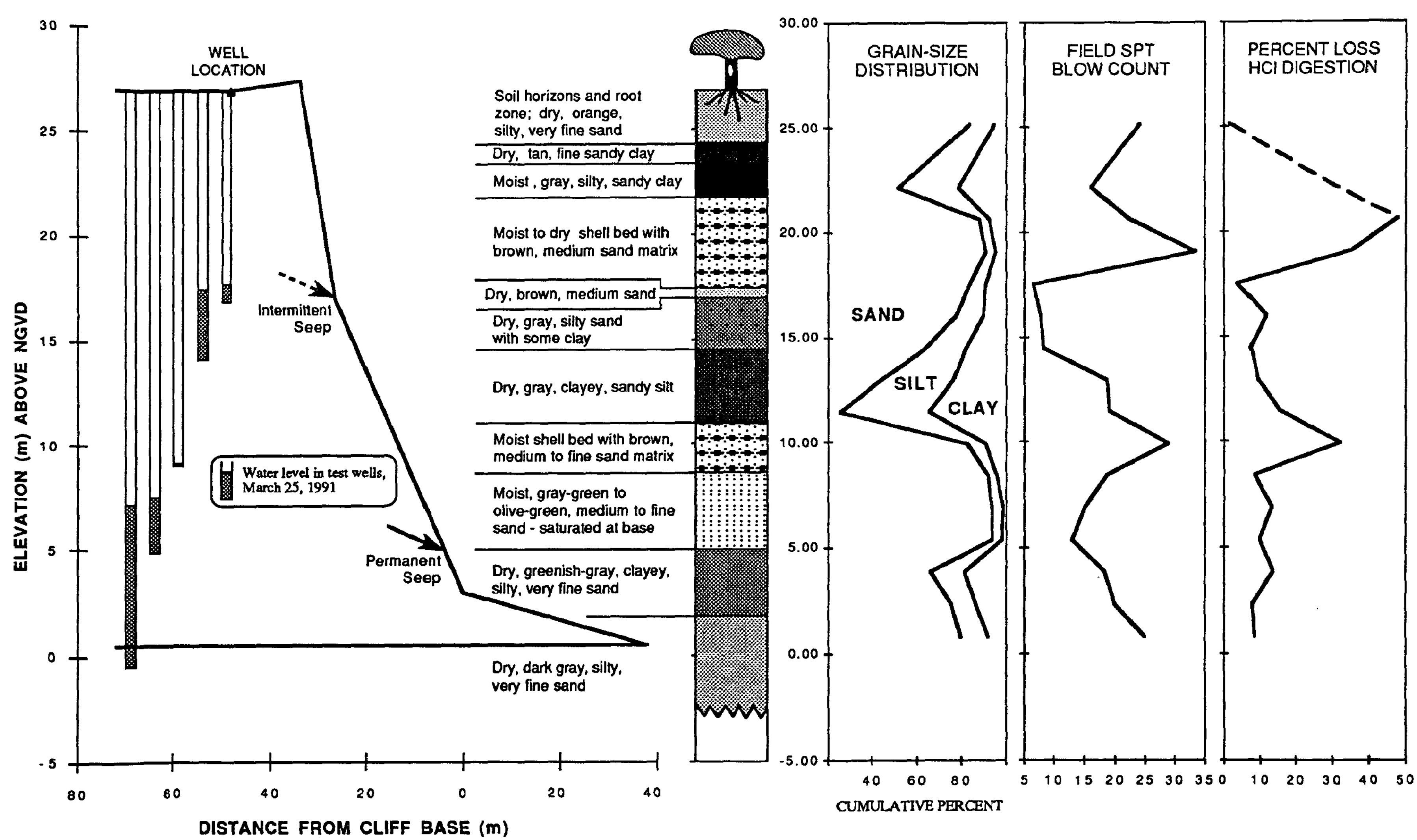


Figure 3.7 Study Site CCSP: Calvert Cliffs State Park

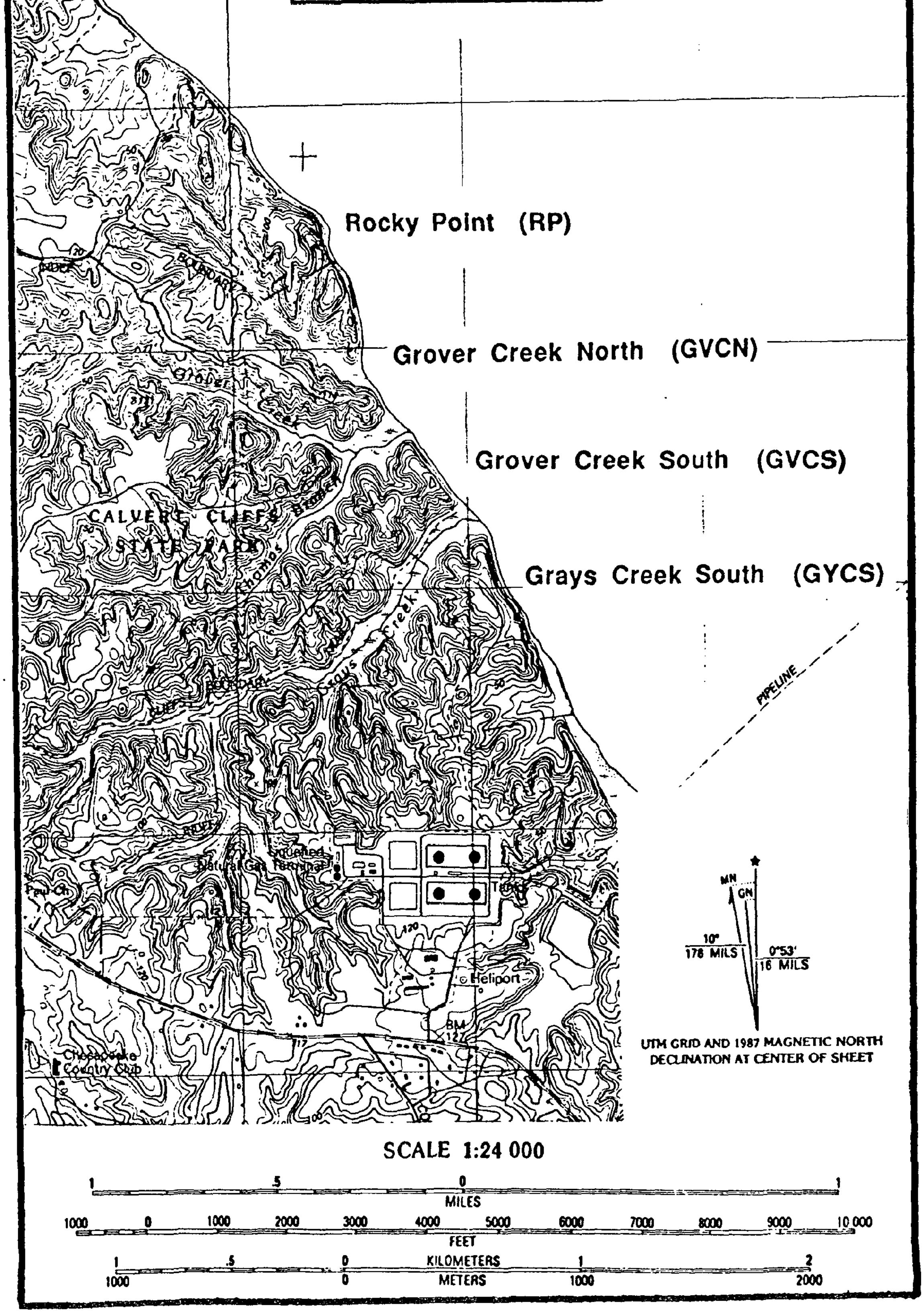


Figure 3.8 Gray's Creek South Slope Profile

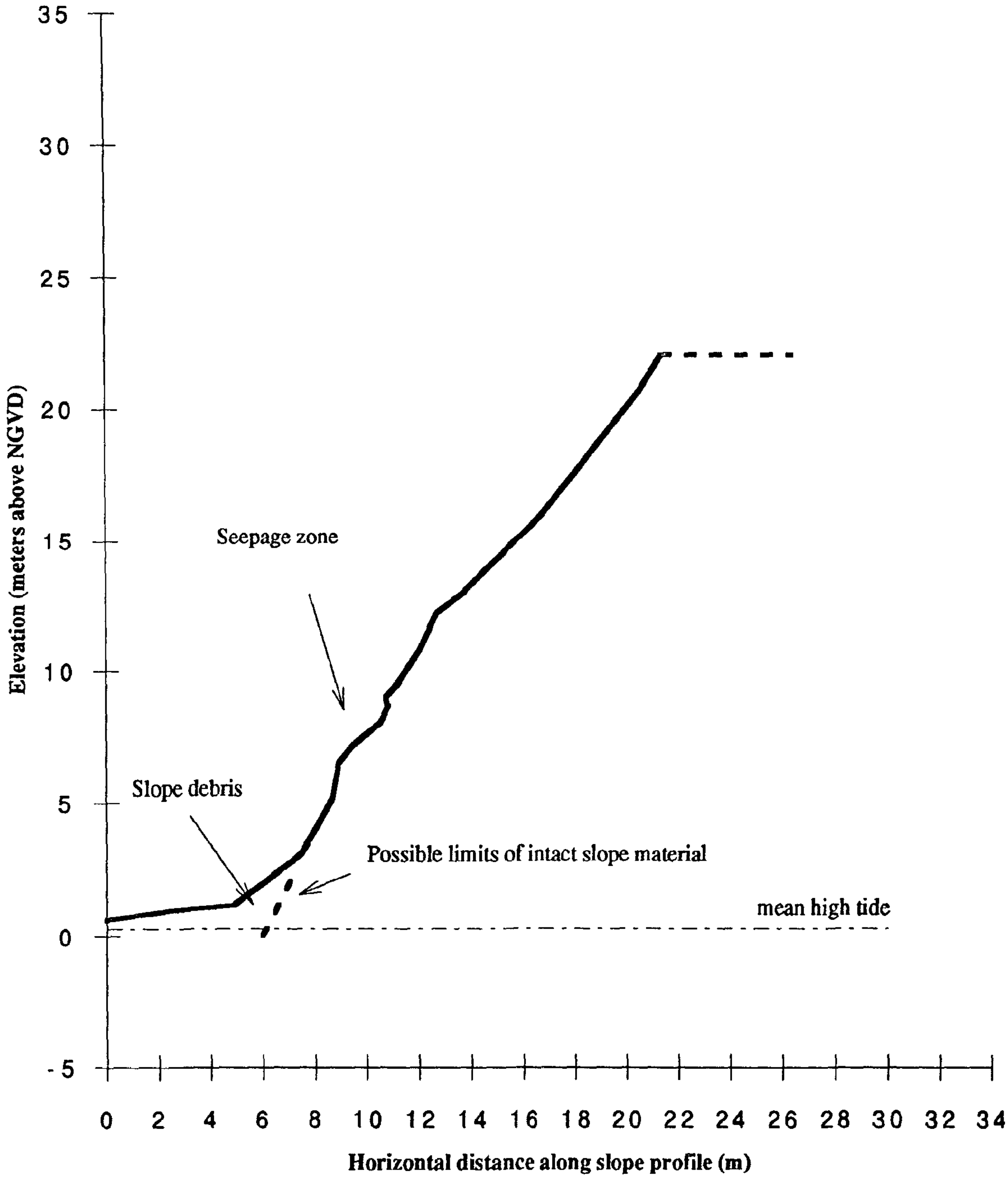


Figure 3.9 Calvert Cliffs State Park Geotechnical Profile

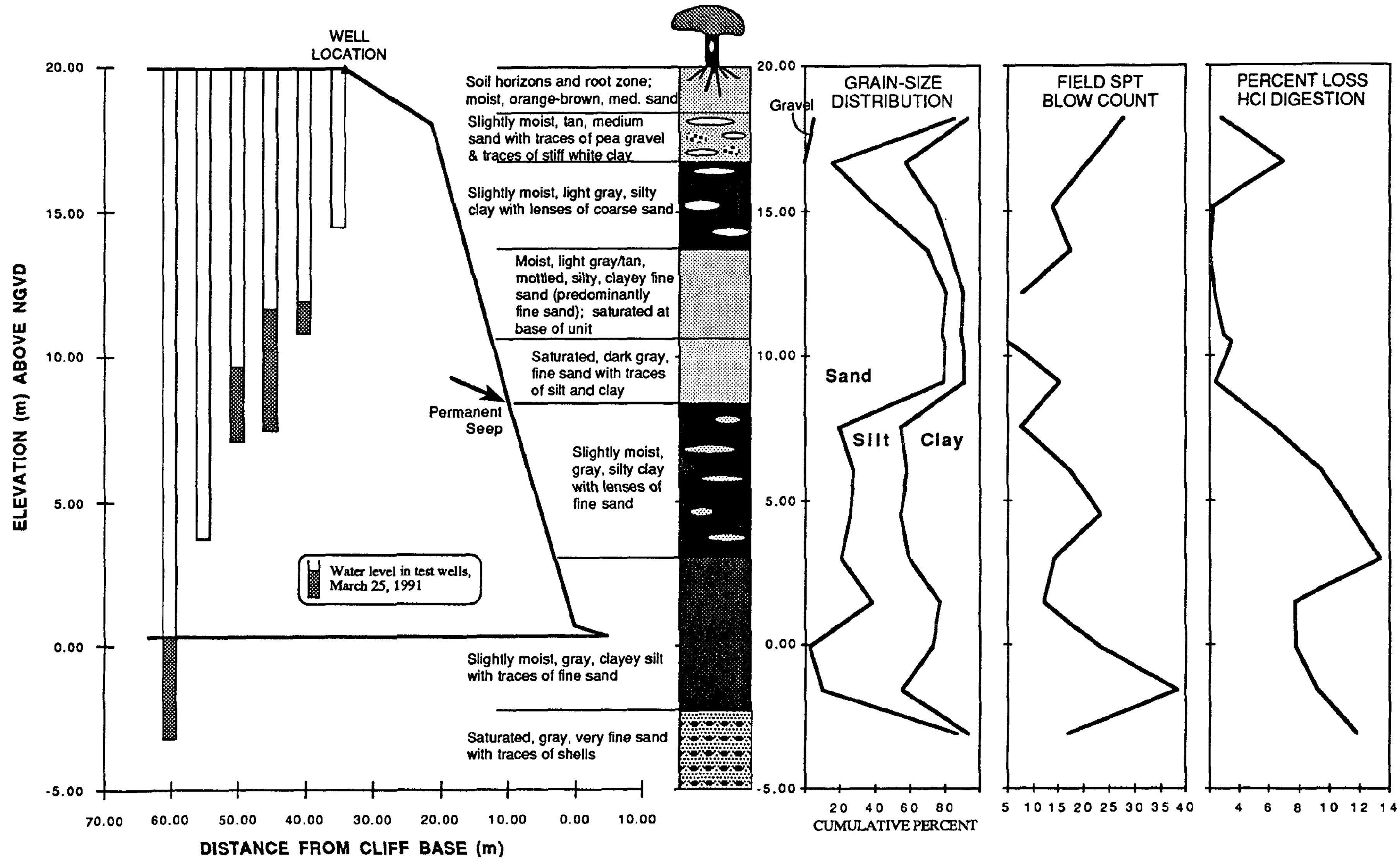


Figure 3.10 Study Site CRE: Chesapeake Ranch Estates

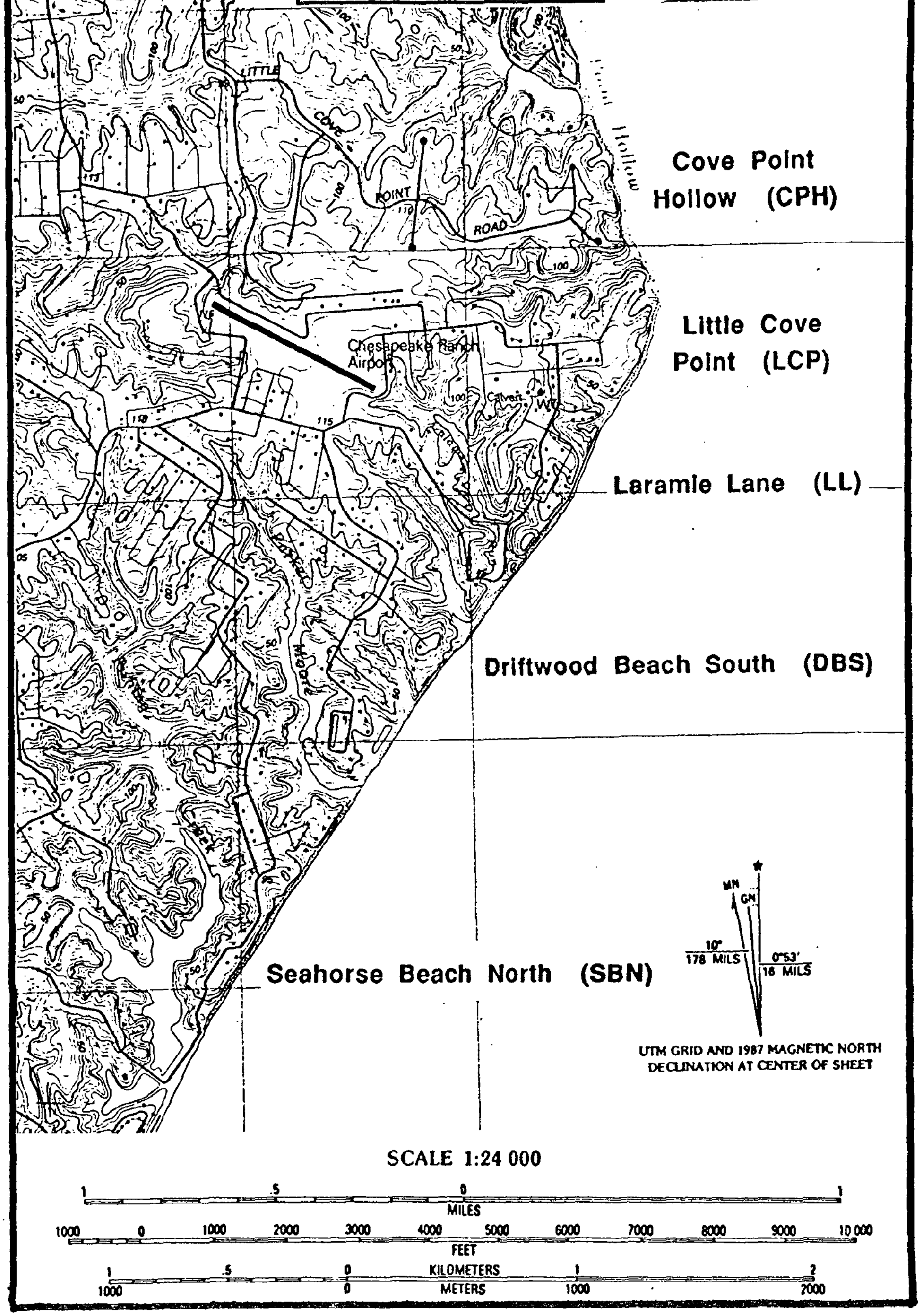


Figure 3.11a Little Cove Point Slope Profile

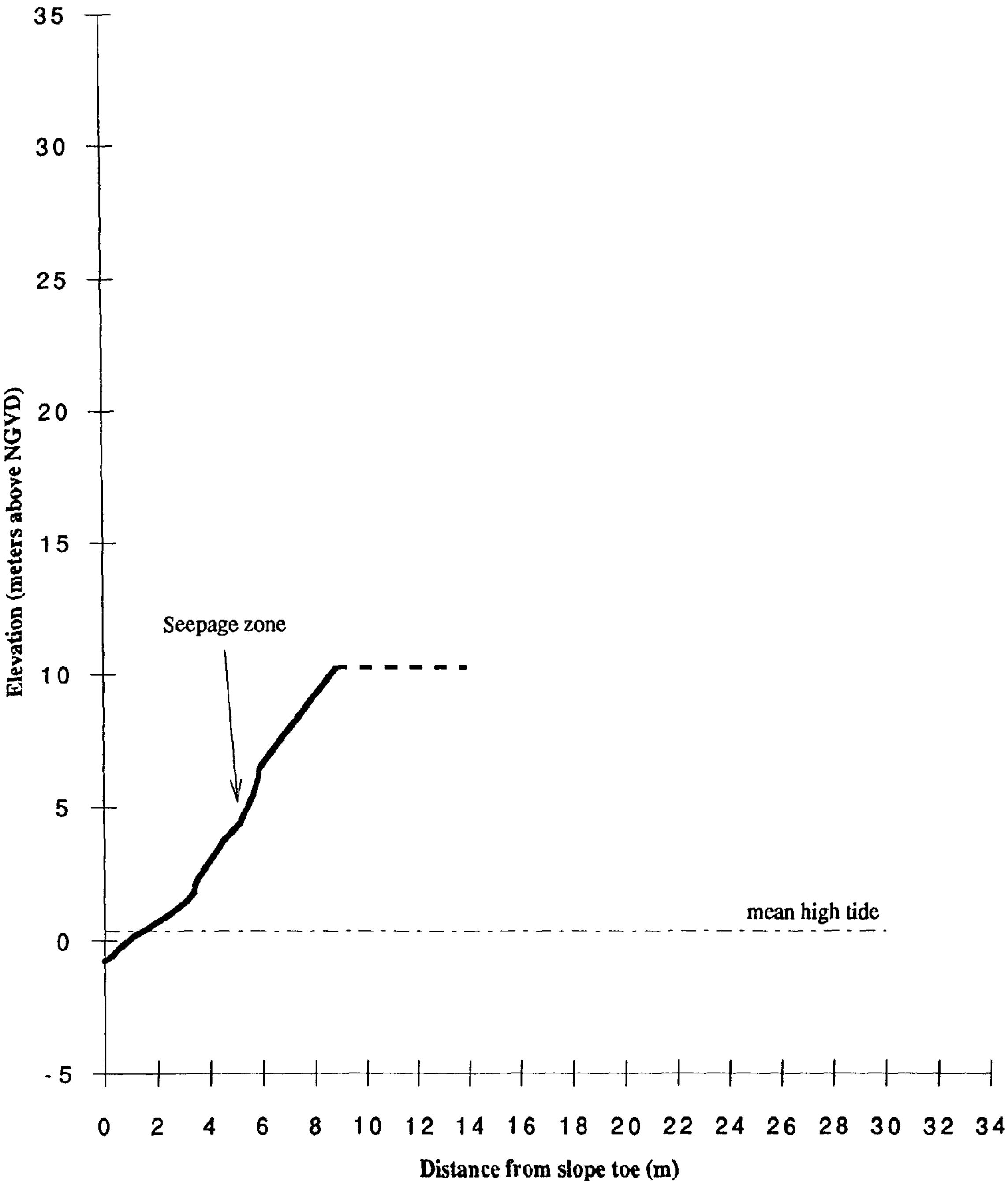


Figure 3.11b Laramie Lane Slope Profile

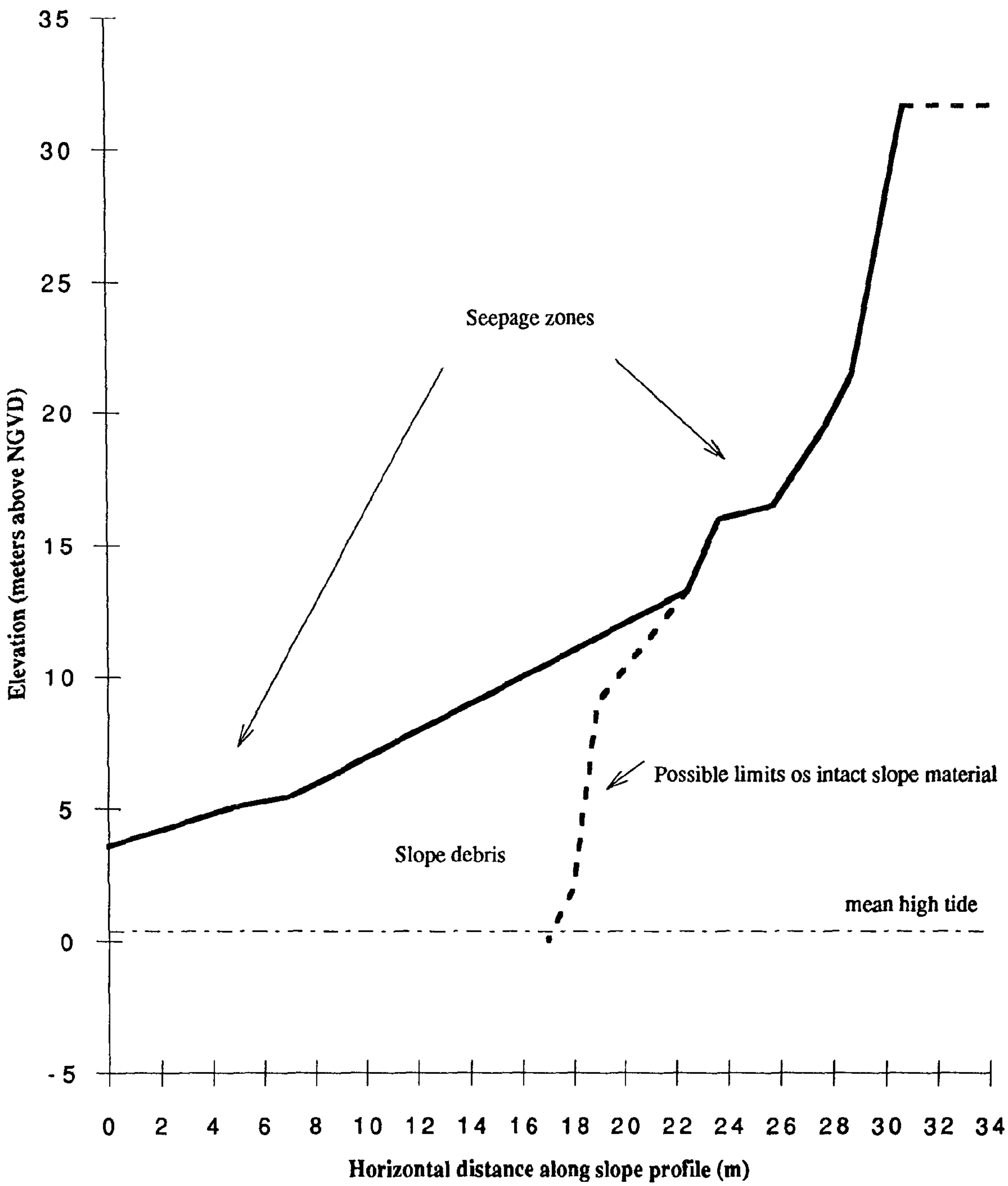


Figure 3.12 Chesapeake Ranch Estates Geotechnical Profile

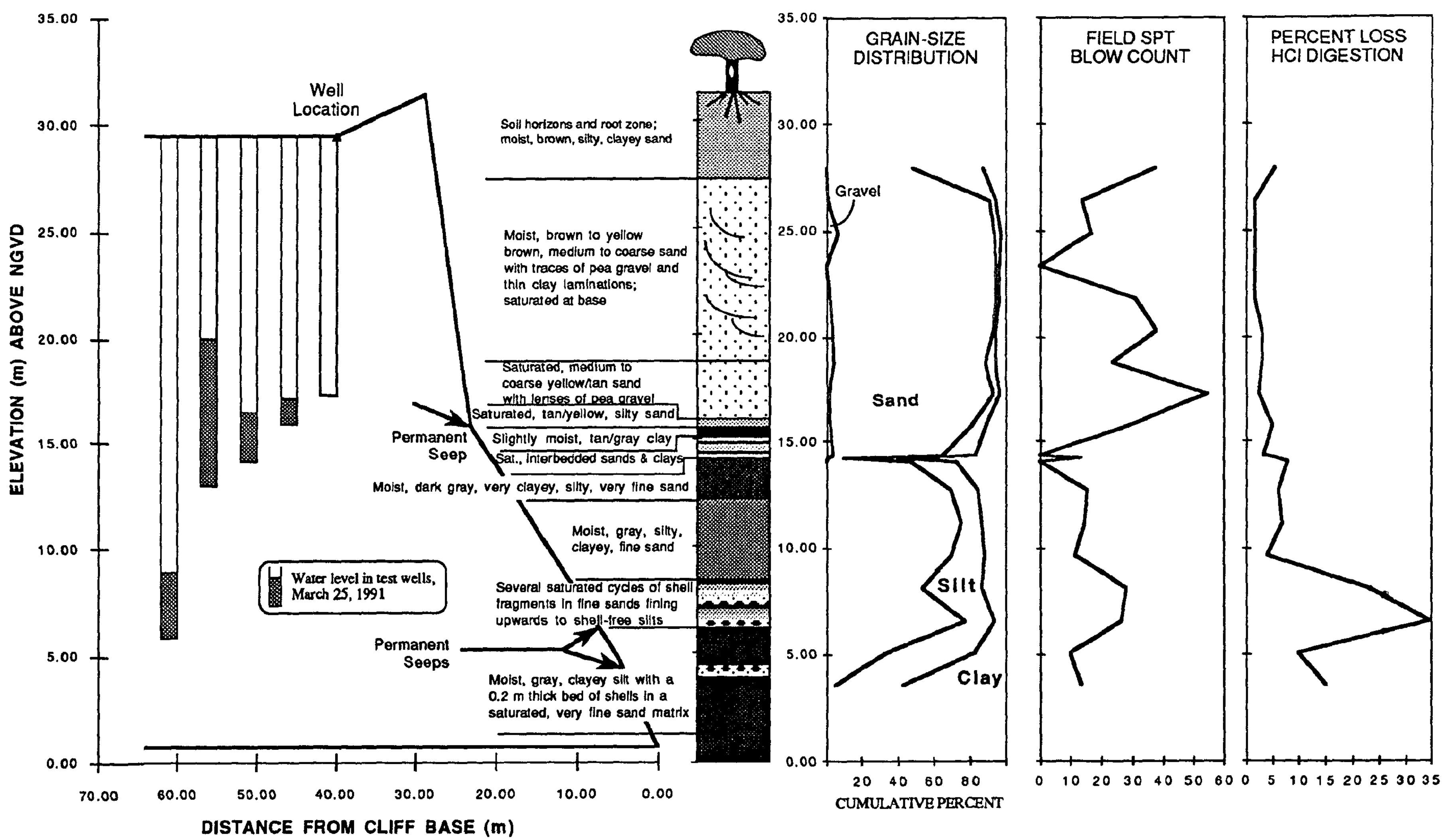
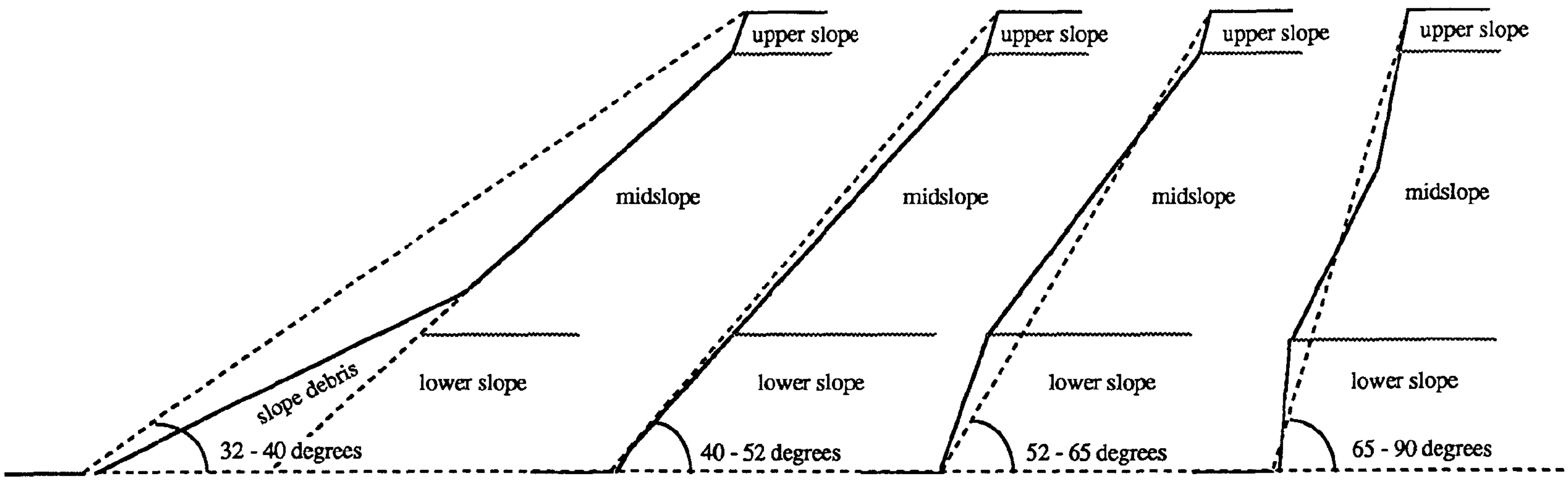


Figure 4.1 - Classification of coastal slopes by undercutting rate and characteristic groups of erosion mechanisms



Type I

$R_b = 0$

Slope debris accumulates at base of slope. Midslope eroded by groundwater seepage and direct runoff of precipitation

Sites: NRLN, NRLS, SCS

Type II

$R_b \ll R_m$

Hydrologic processes dominate erosion of both lower and midslopes

Sites: SCN, LCP

Type III

$R_b < R_m$

Wave undercutting drives shallow sliding and spalling in lower slope. Erosion of the midslope driven by hydrologic processes. Midslope recession proceeds more rapidly than lower slope recession.

Sites: HB, GR, GCS

Type IV

$R_b \approx R_m$

Wave undercutting directly controls erosion of the entire slope via shallow and deep-seated landslides and spalling

Sites: RC, PC, LL

R_b: Rate of recession of the lower slope

R_m: Rate of recession of the midslope

Figure 6.1 Distribution of Coastal Plain Sediments
Around the Chesapeake Bay

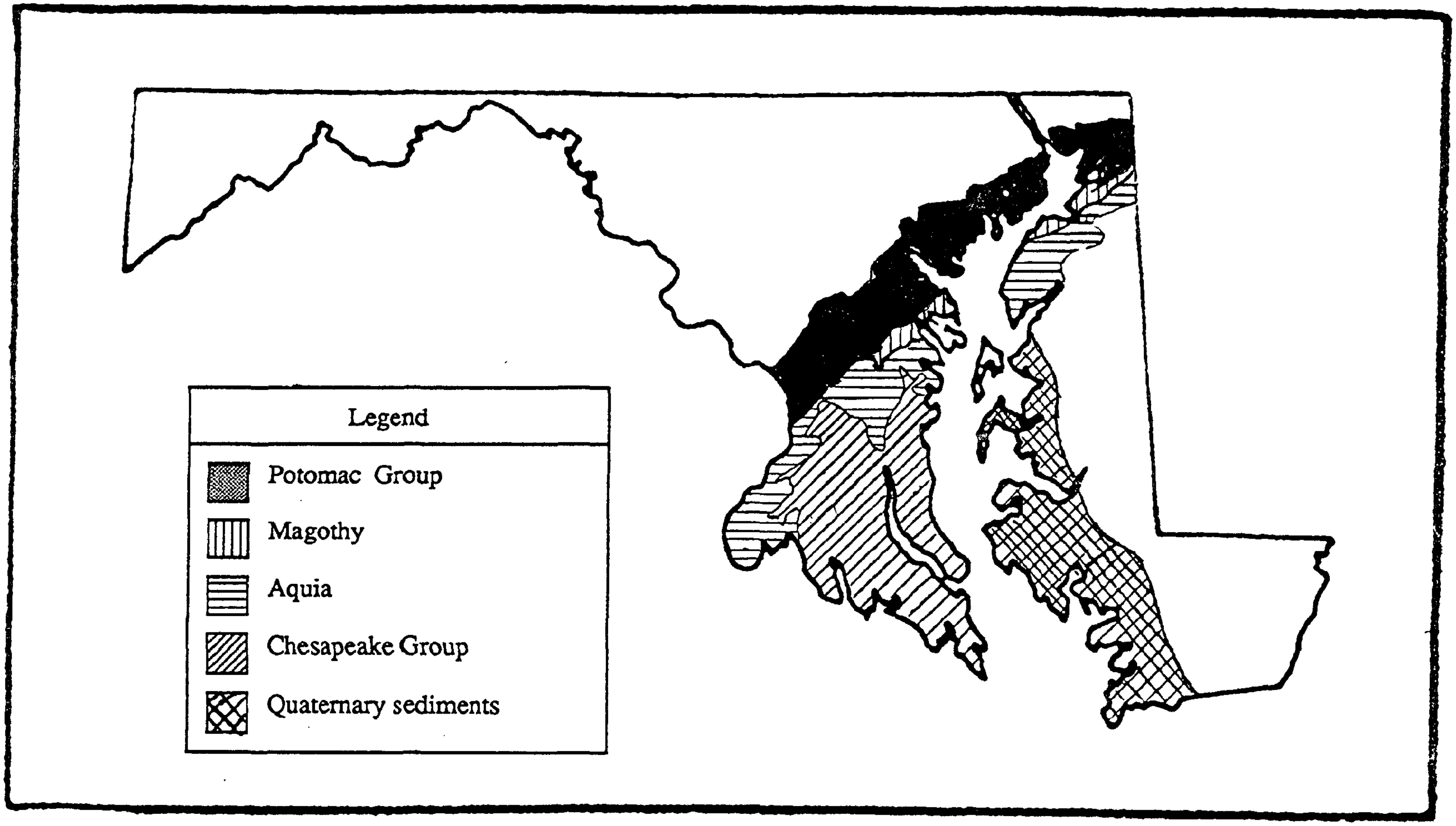
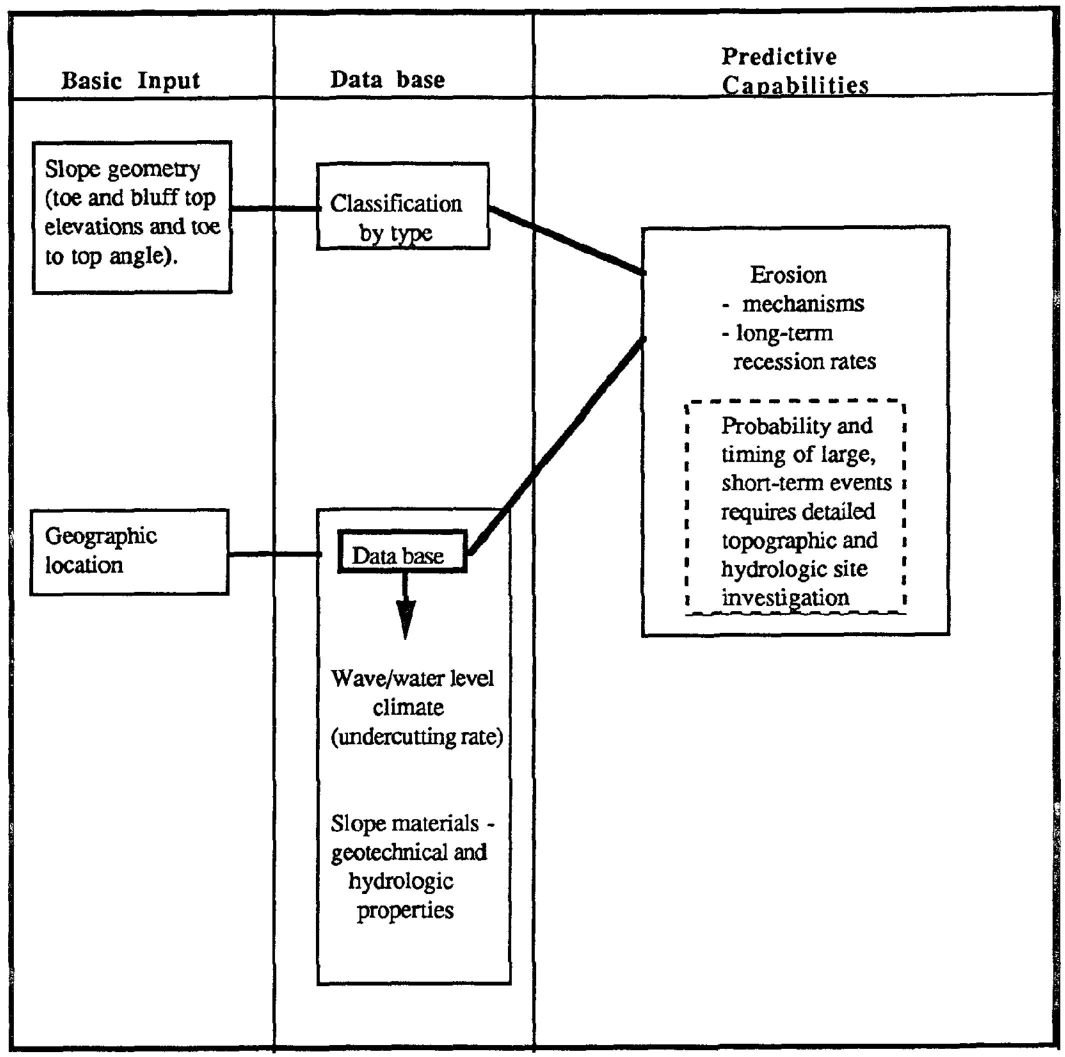
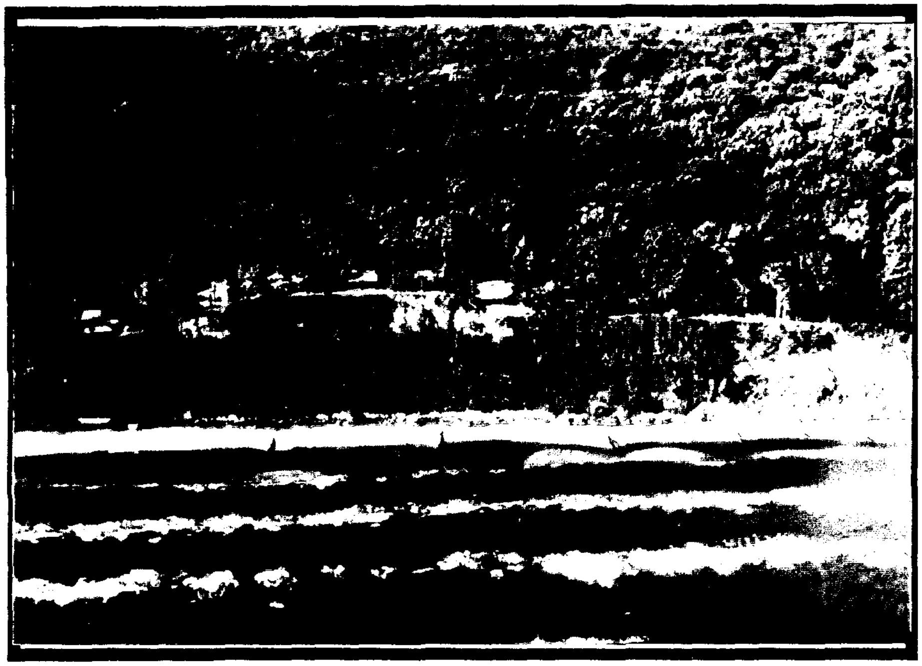


Figure 6.2
- Conceptual model for extending CCSEP results to predict coastal slope erosion along the Chesapeake Bay



Naval Research Laboratory - This photograph shows the boundary between the NRLN and RC subsites. Slope toe protection can be seen on the left side of the picture in the form of a bulkhead. Where the toe is protected, the principal driving mechanism of coastal slope erosion, wave undercutting, is eliminated and the slopes are Type I. Upper slope erosion will continue via hydrologic processes until a stable slope angle from slope toe to bluff top is achieved. Near the center the protection is terminated and the slopes stand nearly vertical. The right side of the photo shows Type IV slopes. The erosion of Type IV slopes is dominated by spalling and shallow sliding and occurs at a rate determined by the wave undercutting rate.

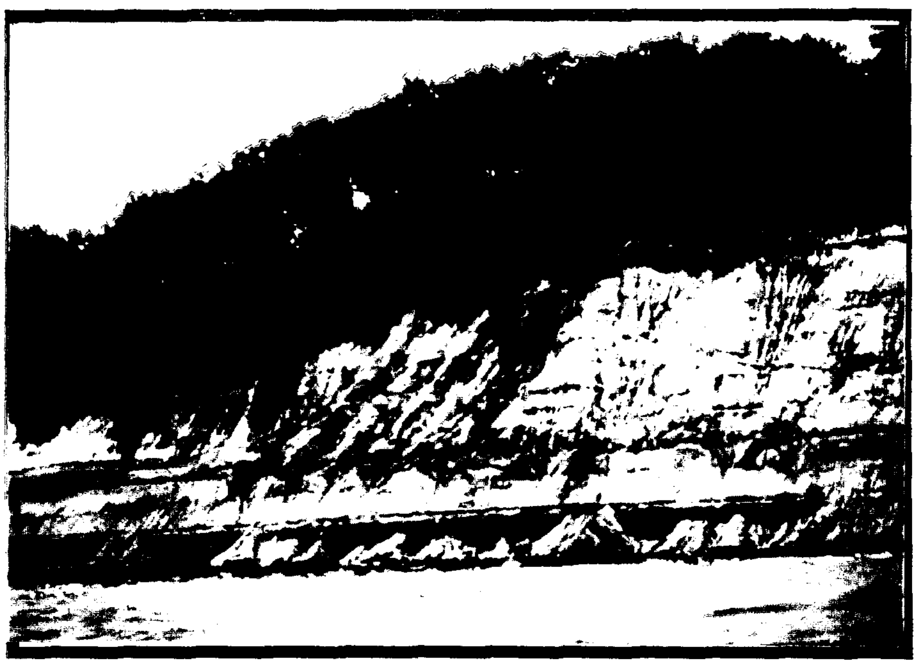
Plate 1



Top photograph - **Scientists' Cliffs North**
Bottom photograph - **Chesapeake Ranch Estates, Little Cove Point**

Both slopes are Type II slopes in that the dominant erosion mechanisms from slope toe to bluff top are hydrologically dominated. Note the lack of wave undercutting at each site.

Plate 2



Top photograph - **Calvert Cliffs State Park, Grays Creek South**
Bottom photograph - **Calvert Cliffs State Park, Rocky Point**

Both slopes are Type III slopes. Here, hydrologic processes control the rate of erosion in the midslope and wave undercutting controls the rate of erosion in the toe zone. The contrast between the midslope and lower slope is clear in this photo; it occurs at the change from dark to light material. Ironstone blocks can be seen in the foreground.

Plate 3

Top photograph - **Calvert Cliffs State Park, Grover Creek South**
Bottom photograph - **Naval Research Laboratory, Randle Cliffs**

Both slopes are Type IV slopes. Here, wave erosion oversteepens the toe zone causing sliding which retrogresses upslope until it reaches the bluff top. Hydrologic processes are still active, but the dominant mechanism of erosion is shallow sliding. Note that at Randle Cliffs, debris cannot accumulate at the slope base because of the water level.

Plate 4

Top photograph - **Scientists' Cliffs, Parker Creek South**
Bottom photograph - **Chesapeake Ranch Estates, Laramie Lane**

Both slopes are Type IV slopes. Spalling due to oversteepening by wave undercutting is evident in the lower slope at Parker Creek. At Laramie Lane, large rotational slides which initiate on a saturated, weak clay in the midslope deliver large debris piles to the slope toe.

Plate 5

Calvert Cliffs State Park, Grays Creek South - This photograph is a close-up of a large spalling event cause by wave undercutting. The slope is a Type IV slope. The lower slope/midslope contact can be clearly seen where the gray lower material meets the orange-brown material above it.

Plate 6